ORIGINAL ARTICLE

Evaluating E-slot Microstrip Antenna for Breast Cancer Hyperthermia Treatment

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ABSTRACT

Introduction: Hyperthermia is a cancer treatment that involves elevating the temperature of the tumuor tissue to a range of 40°C to 45°C to denature protein and shrink the tumour while minimising damage to surrounding healthy tissue. Nonetheless, a significant challenge in hyperthermia treatment is achieving precise heating in the target tissue because its dielectric properties cause uneven heat distribution. Various antenna designs have been explored to improve this aspect, but limited studies have applied E- slot microstrip antenna in breast cancer hyperthermia treatment. E-slot microstrip antennas are widely used in communication because of their enhancement in directivity, gain and return loss. However, its potential in hyperthermia treatment applications has not been fully realised. Therefore, this study aims to develop E-slot microstrip antenna and evaluate its performance characteristics for hyperthermia. **Materials and methods:** Breast phantom and E-slot microstrip antenna were developed, analysed, and verified in Electromagnetic Simulation software (SEMCAD X). The fitting tool used to determine the dielectric properties was based on the Gabriel database. It highlights that the tumour has a higher relative permittivity and conductivity than healthy tissue. **Results:** The E-slot microstrip antenna demonstrated enhancement over non-slot design with low return loss, directivity improvement of 16.4%,13.2% and 8.1%, gain increases of 4.5%,10.1% and 4.8%, Specific Absorption Rate (SAR) peak enhancement of 82.8%, 17 % and 36.4% for T1, T2 and T3, respectively. The SAR distribution with the E-slot microstrip antenna showed heat concentrated at the tumour. **Conclusion:**Hence, the E-slot microstrip antenna has significant potential for effective hyperthermia treatment.
Malaysian Journal of Medicine and Health Sciences (2025) 21(SUPP11): 126-134.doi:10.47836/mjmhs.21.s11.18

Keywords: Hyperthermia, Specific absorption rate, Slot microstrip antenna, Penetration depth, Tumour

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INTRODUCTION

Breast cancer is one of the most common cancers worldwide among females.According to the WHO in 2022, approximately 2.2 million new cases of breast cancer were reported. Globally, the mortality rate of breast cancer was about 6.9% in the year 2020 (1), but this figure increased to 15.4% in 2022, representing a more than two-fold rise. In Malaysia, breast cancer has an even larger effect, contributing to 21.4% (2) of cancer-related deaths among females, indicating the importance of improving breast cancer treatment. The most common treatment for breast cancer involves a combination of surgery, radiation, and chemotherapy.

However, there are tumour cells named as hypoxic cells that exist in a tumour environment and are resistant to radiotherapy and chemotherapy. This tumour cell type leads to an aggressive cancer behaviour (3,4). Hyperthermia can be introduced to address tumour hypoxia. Hyperthermia is a therapeutic technique in cancer treatment that involves elevating tissue temperature from 40°C to 45°C for 30-60 minutes while causing a minimal effect on the healthy surrounding tissue (5).Therefore, antenna development is crucial in engineering aspects to ensure the effectiveness of hyperthermia treatment.

Researchers have developed antenna designs to address these issues and optimise heat distribution to the target tissue. For instance, the applicator used a microstrip patch design, which is widely used because of its low profile and lightweight structure. Microstrip antenna design depends on frequency selection (6,7). Slot antennas are designed to deliver focused electromagnetic energy to treated tissue to enhance the effectiveness of hyperthermia treatment (7,8).The challenge in hyperthermia treatment is to control the distribution of heat to minimize unwanted hotspots, which result in excessive heat to the target area (9,10).

Several studies have revealed that integrating slots to microstrip patch antennas enhances the effectiveness of hyperthermia treatment. Previous studies used various slot designs, such as T-slot, elliptical slot, rectangular slot, cross slot, L-slot, and circular slot. Research claimed improved antenna performance in terms of gain, heating pattern, bandwidth, impedance matching and return loss. The effect of unwanted heat (hotspots) on healthy tissue was minimised (11,12).However, achieving consistent heat distribution and minimising hotspots remains significant challenge because of variations in tissue properties.

A recent research has investigated the performance of antennas with and without slots. The microstrip antenna with slot showed improved return loss and SAR (13). Another work (15) described how slot microstrip antennas performed in terms of bandwidth and penetration depth improvement. The performance of slot antenna was better than without slot, especially in term of penetration depth and SAR distribution (15,16). Furthermore, simulations and experimental studies of slot antenna confirmed the effectiveness of hyperthermia (8,12) Nevertheless, a major challenge in hyperthermia is to ensure that the heating region concentrates on the tumour as the tumour size varies. Therefore, proper slot microstrip antenna design is required.

Slots integrated with microstrip patches allow localised energy delivery and design flexibility (7). However, slots, especially those involved in E-slot microstrip antennas, have been rarely explored for hyperthermia applications. E-slot antenna are widely used in other fields, particularly communications(17,18) . In hyperthermia, the E-slot is expected to perform better than the non-slot microstrip antenna in terms of antenna gain, directivity and return loss.

The SAR(peak) also improved, thereby minimising unwanted hotspots and heat concentration/focus on the tumour. Hence, this study aimed to evaluate the effectiveness of E-slot as an applicator for breast cancer hyperthermia treatment. Results will provide a new approach to a simple and effective antenna design for heat delivery in cancer therapy.

MATERIALS AND METHODS

Experimental by simulation

This study utilizes SEMCAD X 14.8.4 software to simulate the heat distribution, which is represented in the SAR distribution. This software is a 3D full-wave EM simulation with Finite Difference Time Domain (FDTD), a powerful numerical tool that simulates electromagnetic (EM) fields to achieve effective hyperthermia treatment.

The research methodology comprises four main parts: the development of the breast phantom and tumour, the development of the microstrip antenna, the integration of the E-slot into the microstrip antenna and EM simulation.

The next section explains the development of the breast phantom and microstrip antenna in detail. The breast phantom consists of three tumour sizes, namely: small, medium, large and is integrated with the chest wall.

Breast phantom and tumour development

The breast phantom developed is based on an Asian bra cup size of C75 (cm). The tumour size is determined from breast cancer mammogram images. Female breast cancer mammogram images were collected from the Sarawak General Hospital. Ethical approval was obtained from the Medical Research and Ethics Committee (MREC), the Ministry of Health, Malaysia. Data are limited to specific geometrical cancer characteristics such as shape, size and tumour position.

A total of 149 breast cancer mammogram images were collected and used for further investigation. The mammogram breast images were divided into two (2) positioning views: mediolateral oblique (MLO) and cranial caudal (CC). MLO represents an oblique or angled view and CC is the position where the breast is viewed from above (19). Both images were used to determine the size of the tumour.

Ground truth with the expert radiologist was carried out to identify abnormal tissue due to cancer before the data analysis. Digital Imaging and Communications in Medicine (DICOM) was used to determine the diameter of the tumour.

Rectangular microstrip development

The rectangular microstrip antenna was designed with substrate RT5800. It has a low-loss dielectric constant. The substrate has dielectric constant, εr=2.2, and loss tangent tanδ =0.0009. The input power is 10 W. The dimension of the rectangular microstrip antenna is based on (20). The microstrip feed line used $\lambda/4$. The transmission line impedance is 50 Ω.

An antenna with a frequency of 2.45GHz is recommended for tumours close to the skin, while those with 915MHz are suitable for deeper tumours (21). The present study utilised the microstrip antenna design, with an operating frequency of 915MHz (22) because the tumuor is located in the middle of the breast phantom.

E-slot rectangular microstrip development in SEMCAD X

The rectangular microstrip antenna is integrated with the slot. A single-layer slot microstrip antenna is used because of its less complication and ease of fabrication compared with a multilayer antenna. The ground plane is placed on the bottom and the patch is placed on the top of the substrate. The E-slot is cut inside the patch to improve the antenna's performance. The dimension of the E-slot is adapted from the U-slot equation and calculated using Eqs.(1) to (3)(23).

Slot length:

$$D = \frac{c}{2f\sqrt{\varepsilon_{reff}}} - 2(L + 2\Delta L - E) \quad (1)$$

c = speed of light
f= frequency
L=length of patch antenna
ε_{reff}=the effective dielectric constant of the substrate

Slot width:
$$C=D*0.75 \quad (2)$$

$$\text{Thickness: } E = F = \frac{\lambda}{60} \quad (3)$$

EM Simulation
SEMCAD X is used for EM simulation to study the interaction between the EM field generated by the E-slot microstrip antenna and the tumour in the breast fat phantom. The output results are displayed in 2D images that show SAR distribution. The setup simulation of the breast phantom and the E-slot microstrip antenna is placed in SEMCAD X, as presented in Figure 1. The E-slot microstrip antenna is directly placed on the breast phantom.

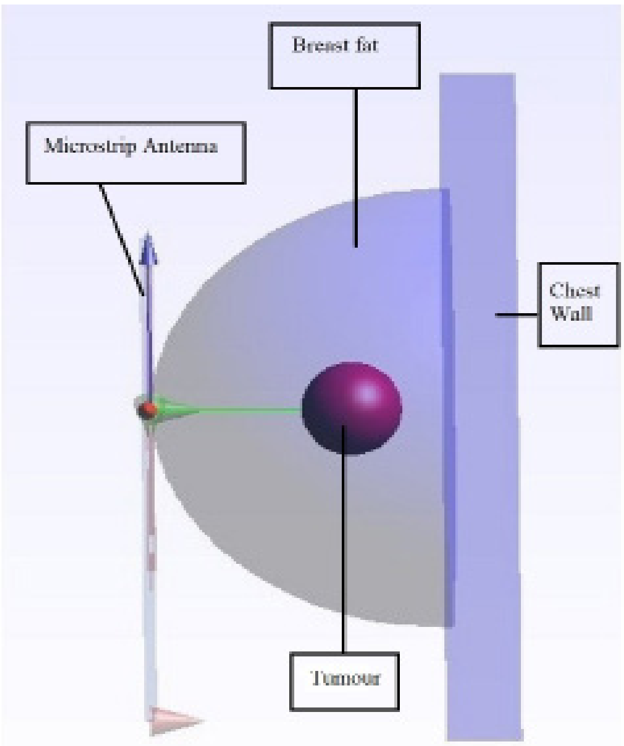

Figure 1: Simulation Setup in SEMCAD X.

RESULTS

SEMCAD X utilizes the Gabriel Tissue Database (GTD), developed by Gabriel in 1966 (23), which is a parametric model commonly used to estimate the dielectric properties of biological tissues. The database is used as a standard reference to determine dielectric properties such as relative permittivity (ε_r) and electrical conductivity (σ) in tissues.

The fitting model uses a dispersive fitting tool to match the measured input at the frequency range of 900MHz-930MHz. The fitting model applies to skin, breast fat, tumour and chest wall to determine the electrical and thermal properties of tissues based on the Gabriel database setting (25). This is to ensure that the model accurately represents the dielectric behaviour.

Tissue permittivity comprises real and imaginary parts. The real part represents the tissue's ability to store electrical energy, while the imaginary part indicates energy loss within the tissue. Both are essential for accurately modelling the breast phantom. The electrical properties of the phantom in Table I are based on the fitting model. The breast phantom is inserted with the tumour and integrated with the chest wall. The descriptions of T1, T2 and T3 are based on previous work (26) and the American Joint Committee for Cancer as follows: T1 is defined as tumour size with a diameter of less than or equal to 20 mm (T1 ≤ 20 mm), while T2: 20 mm < T2 ≤ 50 mm, and T3: T3 > 50 mm (27).

The analysis of tumour size is explained in (22). Surface depth refers to the initial point of tissue where the EM energy begins to be absorbed by the tissue, whereas penetration depth refers to the deepest point where the tissue absorbs EM energy.

Table I: Electrical properties of the phantom

Type of Tissue	Relative Permittivity,	Electrical Conductivity, σ (S/m)
Skin	36	1.464
Breast fat	3.413	0.651
Tumour	43.273	4.738
Chest muscle/wall	28.79	12.883

The surface depth of T1 is 50 mm and the penetration depth is 64 mm; for T2, the surface depth is 48 mm and the penetration depth is 80 mm; for T3, the surface depth is 28 mm and the penetration depth is 90 mm. The difference in surface depth determines the diameter of the tumour, namely T1 = 14 mm, T2 = 32 mm, and T3 =62mm.

In this study, the tumour is situated in a bounding box that provides minimum point (P1) and maximum point (P2) in (x, y, z) axes based on surface depth and penetration depth analysis. The position of T1 in the bounding box of {P(x); -7≤ x ≤ 7, P(y) = 50 ≤ x ≤ 64, P(z)= -7≤ x ≤ 7}; the position for T2 is {P(x); -16≤ x ≤ 16, P(y) = 48 ≤ x ≤ 80, P(z)= -16≤ x ≤ 16}; and T3 is { P(x); -31≤ x ≤ 31, P(y) = 28 ≤ x ≤ 90, P(z)= -31≤ x ≤ 31}. The T1, T2, and T3 positions are displayed in Figure 2.

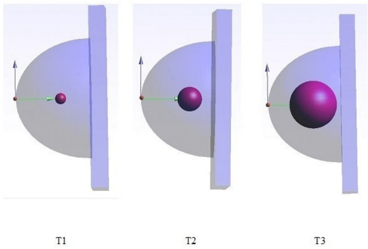

Figure 2: Position of T1, T2 and T3 in the breast phantom.

After the breast phantom, tumour and chest wall are fully developed with electrical properties, a microstrip antenna with a rectangular patch is designed with the thickness substrate RT5880 and patch-based on datasheet (28). The dimension of a rectangular microstrip antenna with 915MHz is 166.68(*l*) x 138.96(*w*) x 1.575(*h*) mm^3. The patch dimension is 110.39(*l*) x 129.51(*w*) x 0.035(*h*) mm^3, as indicated in Figure 3(a).

After the rectangular microstrip antenna is developed, the E-slot is integrated into the microstrip antenna. The E-slot consists of vertical length (D), horizontal length (C), thickness of the horizontal upper arm , lower arm , middle arm, represent in E and vertical thick (F), indicated with E=EU=EL =Emid =F. The dimensions of G, H, I, J and K indicate the symmetric position of the E-slot. The dimensions of C=73 mm, D=98 mm, E=F=6 mm, J=I=25.12 mm, G=H=40mm and K =6.25mm are shown in Figure 3(b).

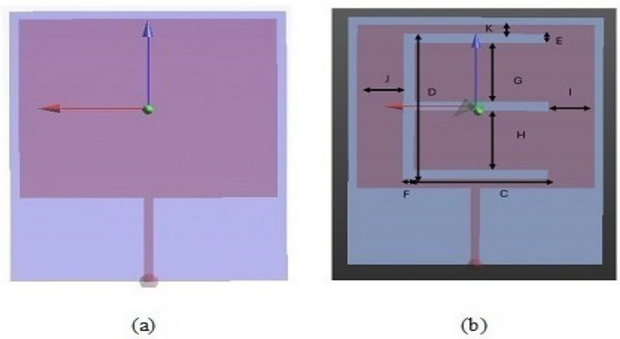

Figure 3: (a) Non-slot microstrip antenna (b) E-slot microstrip antenna.

The E-slot integrates into a rectangular patch antenna in a symmetric position. Symmetrical design helps in balancing the electric field and reduces undesired cross-polarization. Therefore, the E-slot position is placed symmetrically on the patch (low cross-polarized) (29). Integrating the slot into a rectangular patch alters the current density because the slot creates an additional path of current distribution, thereby affecting the antenna performance (15).

High current density enhances power deposition, resulting in more concentrated heating of the target tissue. The directivity and gain of the antenna improved, meaning the EM energy becomes more concentrated and focused toward tumour (7). The return loss is also reduced to ensure that most of the EM energy is absorbed by the tumour rather than reflected (30).

The slot can control heating patterns and SAR, which is represented by the interaction between EM waves in tissue and heat absorption in treated tissue. SAR measures heat absorption in mass in treated tissue in W/kg or mW/g (31).

The findings in Table II compare the performance of a non-slot and E-slot microstrip antenna in terms of directivity, gain, return loss and radiation efficiency. SAR (peak) and penetration depth are based on the SAR distribution outcome. The finding highlights the impact of the E-slot microstrip antenna on gain, directivity, return loss, radiation efficiency, penetration depth and SAR(peak).

Table II: Comparison of antenna performance in non-slot slot and E slot microstrip antenna

Characteristics	Non- Slot	With E- slot
T1		
Directivity(dBi)	6.13326	7.14145
Gain(dBi)	3.857	4.492
Return Loss(dB)	-0.00643	-4.38853
Radiation Efficiency	0.592	0.5433
SAR(peak)(mW/g)	5.1578	9.4283
Penetration Depth (mm)	66.5	64.5
T2		
Directivity(dBi)	6.45944	7.31097
Gain(dBi)	4.29758	4.73181
Return Loss(dB)	-0.006169	-5.14705
Radiation Efficiency	0.607874	0.552185
SAR(peak)(mW/g)	24.667	28.86
Penetration Depth(mm)	71.6	71
T3		
Directivity(dBi)	6.80551	7.35922
Gain(dBi)	4.98009	5.22109
Return Loss(dB)	-0.00529	-4.35143
Radiation Efficiency	0.656838	0.611205
SAR(peak)(mW/g)	35.393	48.263
Penetration Depth(mm)	67	66.6

Figure 4 indicates that the E-slot antenna performs better in parameters, particularly in directivity, gain, return loss and SAR(peak). The improved heating performance is reported to be mainly due to the shape and slot structure of the antenna (32).

The enhancement results in Figure 4 were then verified with the SAR distribution of T1, T2, and T3 for both non-slot and E-slot microstrip antennas, as demonstrated in Figure 5. The SAR distribution represents the heat absorbed by the tumour and healthy tissue. It shows that the E-slot microstrip antenna focuses more on the tumour and has a uniform radiation pattern in all T1, T2 and T3 conditions. E-slot microstrip antenna reduces the unwanted heat that spreads to the healthy tissue. These results confirm that the E-slot microstrip antenna delivers focused heat on the tumour with minimal effect on surrounding healthy tissue.

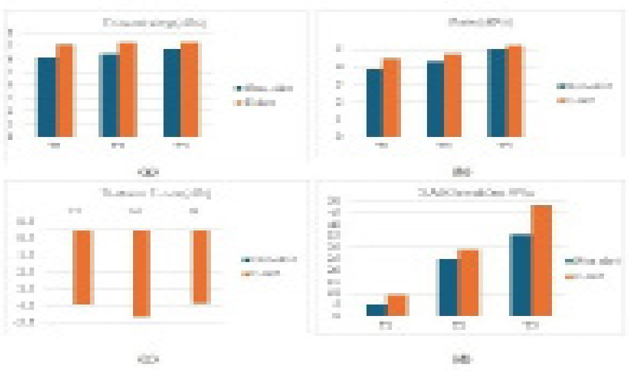

Figure 4: (a) Directivity (b) Gain (c) Return Loss (d) SAR(peak)

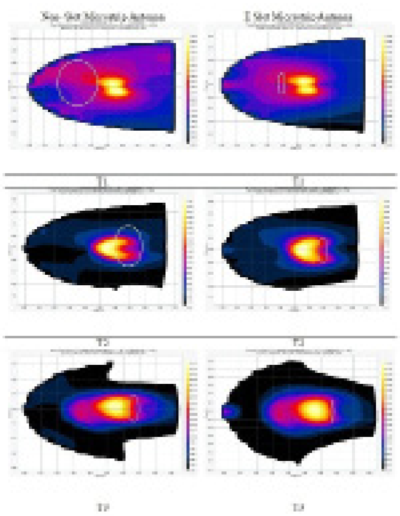

Figure 5: SAR distribution in Non-Slot and E-slot microstrip antenna under T1, T2 and T3 conditions.

DISCUSSION

The finding in Table I, supported by the previous study, revealed that cancerous tissue/tumours contain up to 27% more water than healthy tissue and are considered to have high capacitance. Water can store more electrical charge in thermal energy and dissipate heat more efficiently when exposed to an electric field (33). In general, tumours are rich in blood vessels and have higher permittivity and conductivity than healthy tissues (34,35).

As mentioned in the methodology, RT5880 was used as the antenna substrate. The implementation of RT5800 improved several performance aspects, including return loss, increased gain and enhanced directivity (36). This improvement is because RT5880 (εr=2.2) has a low dielectric constant compared to substrates like FR4 (εr=4.4) and RO4003 (εr=3.55)(37).The selection of RT5880 aligns with recent research that emphasizes the importance of utilizing an appropriate substrate to enhance antenna performance in hyperthermia applications.

Table II displays the comparative analysis of non-slot and E-slot microstrip antennas. The E-slot antenna consistently exhibits higher directivity and gain under T1, T2 and T3 conditions. The directivity of the E-slot microstrip antenna is 7.14145 dBi compared to the non-slot, which is only 6.1332 dBi compare to non-slot. In T3, directivity is improved from 6.80551 dBi for the non-slot to 7.35922 dBi with the E-slot antenna. The increase in directivity indicates that the E-slot microstrip antenna focuses EM energy more locally while minimising the effect on surrounding healthy tissue (6).

The gain improved from 3.857 dBi to 4.492 dBi, from 4.29758 dBi to 4.73181 dBi and from 4.98009 dBi to 5.22109 dBi for T1, T2 and T3, respectively, when E-slot compared to non-slot.. The higher gain reflects the antenna's improved ability to radiate more power in a specific direction and contribute more efficient energy delivery, which is essential for ensuring sufficient tumour heating (38).

The E-slot microstrip patch demonstrated a decrease in return loss compared with the non-slot microstrip antenna under all conditions (T1, T2 and T3). Hence, the E-slot microstrip antenna has better impedance matching and reduces signal reflection.

The reduction in radiation efficiency in the E-slot microstrip antenna is due to power loss, which includes conductor and dielectric losses. Conduction loss occurs because of the resistance of antenna material, which causes power dissipation as heat. Dielectric loss is caused by substrate material properties that can absorb EM energy (39). Radiation efficiency measures the ratio of power radiated in tissue over input power (Prad/Pin).

In hyperthermia, the focus is not only on radiation power but also on maximising the delivery of power into the tissue. Reducing radiation efficiency can indicate more input power absorbed by the tissue (40), mainly contributing directly to heat of tumour. The heat absorption is reflected in SAR distribution, demonstrating the effectiveness of energy delivery to the tumour as in Figure 5.

SAR determines the amount of heat absorbed by the tumour (31). SAR(peak) refers to the highest localised SAR average, typically 1 g or 10 g volume of the tumour as specified by IEEE and IEC62704 (41). The tissue volume defines the highest energy concentration within the tumour (25).

Table II shows that the SAR(peak) increases in the E-slot microstrip antenna compared with the non-slot antenna under all T1, T2 and T3. This increment in SAR(peak) indicates that the E-slot microstrip antenna can focus more energy on the tumour and reduce the effect on the surrounding healthy tissue. The effect of reduced unwanted hotspots is illustrated in Figure 5.

The penetration depth of the E-slot microstrip antenna is slightly lower than that of the non-slot antenna. It decreases from 66.5 to 64.5 mm in T1, from 71.6 mm to 71 mm in T2 and from 67 mm to 66.6 mm in T3. However, this slight reduction does not significantly affect the antenna's ability to increase the effectiveness of hyperthermia treatment. The E-slot microstrip antenna improved gain, directivity, return loss and SAR (peak) and thus could be an option for precise and concentrated heat energy to tumours.

Figure 4 illustrates the improved directivity, gain, return loss and SAR(peak). The graph indicates that the E-slot antenna performs better in these parameters. Directivity is improved by about 16.43%, 13.18% and 8.14% for T1, T2 and T3, respectively. Meanwhile, gain is improved by 4.52% (T1), 10.10% (T2) and 4.84% (T3). SAR (peak) is improved to 82.8% for T1, 17% for T2 and 36.4% for T3. These findings align with those of a previous study, which demonstrated that applying the E-slot in antenna provides better performance(42–43) and improves return loss, bandwidth, gain and directivity.

The 2D SAR distribution displayed in Figure 5 illustrates the region discovered by heat. The comparison is between the non-slot and the E-slot microstrip antenna in T1, T2 and T3. Heat distribution appears to be more spread out and less concentrated in the tumour region in the non-slot antenna. This finding indicates that more heat is scattered and low-focus heat is distributed to the tumour.

Integrating the E-slot into a rectangular patch creates an additional path of current distribution (15). As a result, the high current density enhances power deposition, causing the heating to be concentrated on the target tissue.

In evaluating the E-slot microstrip antenna for hyperthermia treatment, the SAR distribution is more focused and concentrated at the tumour region than that in the non-slot microstrip antenna. The SAR (peak) demonstrates that the E-slot microstrip antenna achieves consistently higher SAR (peak) across all T1, T2 and T3 than the non-slot microstrip antenna.

The E-slot microstrip antenna has SAR (peak) values of 9.4283 mW/g and 28.86 mW/g, 48.26 mW/g for T1, T2 and T3, respectively. The non-slot microstrip antenna achieves SAR (peak) of 5.1578 mW/g for T1, 24.667 mW/g for T2 and 35.393 mW/g for T3.

The maximum temperature reached during the simulation is 45 °C, corresponding to the SAR (peak). The relationship between SAR and temperature is given by the equation SAR = $C\Delta T/\Delta t$, which shows that SAR is directly proportional to temperature, T and inversely proportional to time duration, t (44). As the SAR(peak) increases, the time required to achieve the desired therapeutic temperature decreases. Hence, the E-slot microstrip antenna may reduce the treatment time for hyperthermia due to its higher SAR(peak). The temperature used in this study ranges from 40°C to 45°C to ensure the treatment stays within safe and effective therapeutic limits (45).

The hyperthermia treatment depends on temperature and duration of exposure. Prolonged treatment duration allows the temperature to keep increasing, while the tumour continues to dissipate heat. The accumulated heat disrupts the tumour cell, eventually causing the tumour to shrink and die. However, excessive heat can lead to thermal damage to surrounding healthy tissue (46). Therefore, it is essential to minimised treatment time while still achieving the desired therapeutic outcome.

Enhancing SAR is important in hyperthermia treatment because it directly contributes to effective heat localisation. Therefore, heating should be focused within the tumour while minimising unwanted hotpot exposure on surrounding tissue. Localisation also increases energy absorption in the tumour and improves the overall efficacy of hyperthermia treatment (47). The enhancement of SAR is achieved in the E-slot microstrip antenna.

Overall, the outcome for the E-slot improved, especially in directivity, gain and return loss. By improving the directivity, the antenna focuses transmitted heat in the target tissue, which is the tumour, making the radiation of heat more uniform in all directions (48). Gain is a combination of antenna directivity and efficiency. The return loss minimizes the reflection of unwanted heat or energy. All of these factors contribute to increasing the effectiveness of hyperthermia treatment.

CONCLUSION

The E-slot microstrip antenna performs better than the non-slot microstrip antenna. The antenna used RT5800, which utilized and demonstrated better antenna performance. By integrating the E-slot, the microstrip antenna exhibits improved characteristics such as high gain, directivity and minimised return loss. The increased gain suggests that the antenna can radiate large amounts of heat toward the tumour. Meanwhile, high directivity indicates a focused radiation pattern, allowing for improved tumour targeting. Additionally, the reduction in return loss results in low reflection and focused heat on the tumour.

The antenna performance is validated with SAR distribution, where less heat is scattered on healthy tissue and heat is concentrated more in the tumour, thereby minimising unwanted hotspots in the E-slot microstrip antenna. The SAR(peak) value in the E-slot microstrip antenna is higher than that of the non-slot microstrip antenna, indicating that less time is required for hyperthermia treatment in the former. Therefore, developing E-slot microstrip antennas offers a promising solution for effective breast cancer hyperthermia treatment. The optimisation of the E-slot microstrip antenna should be conducted in future studies to enhance the treatment outcome of hyperthermia.

ACKNOWLEDGEMENT

The author gratefully acknowledges the guidance, support and encouragement provided by UNIMAS and UiTM Sarawak throughout this study. The access to research facilities and resources provided by both institutions offered by both institutions was essential in the successful completion of this work. The author would like to thank the Medical Research and Ethics Committee, Ministry of Health, Malaysia, for providing mammogram breast cancer images from Sarawak General Hospital with reference letter KKM/NIHSEC/P20-578(12).

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