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FDTD Computational Simulation for SAR Observation towards Breast Hyperthermia Cancer Procedure

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ABSTRACT

The radiation absorption distribution of electromagnetic energy into the breast phantom is of fundamental importance in understanding its therapeutic capability emitted by the microstrip applicator for non-invasive hyperthermia procedure. In this paper simple microstrip applicator with rectangular shape is presented. Different operating frequency were investigated to observe radiation absorption distribution, which is measured through specific absorption rate (SAR) parameter. The operational frequency was 915MHz and 2450MHz, the industry, scientific and medical (ISM) frequency range. As simulated by using the finite difference time-domain (FDTD) computational simulation which is known as SEMCAD X solver, the results shed an interesting observation on the SAR when frequency varies, which is shown by the transformation onto the penetration depth and focusing capability onto the breast area to be treated.

Keywords: Non-invasive, hyperthermia, SAR, microstrip applicator

INTRODUCTION

Evolution in computational electromagnetics has significantly contributed towards the rapid development of novel antenna designs. The computational electromagnetics is presented by various numerical techniques include the method of moments (MoM), finite element method (FEM) and the finite difference time-domain (FDTD) method, which have been well developed over the years. As a consequence, numerous commercial software packages have emerged. With a powerful personal computer and advanced numerical techniques or commercial software, complex engineered electromagnetic materials in antenna designs can be arrived at.

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Nomenclature

MoM is method of moment

FEM is finite element method

FDTD is finite difference time-domain

SAR is specific absorption rate

ALARA is as low as reasonably achievable

EFS is effective field size

E field is electric field

Therefore, the exploration on antenna application in medical therapy is conducted with FDTD computational packages known as SEMCAD X to obtain the specific absorption rate (SAR) outcomes on the shape, depth penetration and focusing capability of the electromagnetic antenna. In this study , microstrip antenna or applicator was used. The medical therapy studied is known as hyperthermia cancer procedure. Hyperthermia is an alternative procedure for cancer, using slightly high heat about 41°C – 45°C in order to denaturate the cancer tissue into the necrotic tissue (Choi, Kim, Kim, & Yoon, 2014; Nguyen, Abbosh, & Crozier, 2015; Rajendran, 2015). The electromagnetic fields have a great influence on the behaviour of all the living systems. The radiation contributes from the electromagnetic may results harmful health effect, especially in case of long exposures to low such as power system. This imposes by as low as reasonably achievable (ALARA) principle (Plewako, Krawczyk, & Grochowicz, 2003). Nevertheless, some benefits can be taken from the effects of the electromagnetic fields on the living being such as hyperthermia cancer procedure, which is discussed and investigated further in this work. As in industrial application, the electromagnetic computation is utilised at early investigation as to allow a better knowledge of the phenomena, and for the purpose of this research, it is allows an optimised design for hyperthermia. SAR is observed as to provide the information on two essential parameters for the hyperthermia, which are penetration depth and focusing capability either both parameters are satisfied enough or vice versa.

Hyperthermia can be either invasive or non-invasive and depends on the position of hyperthermia applicator i.e. weather it is penetrating the body through the skin or radiate from outside the body. Since, non-invasive method may produce less side effects, the investigation of this method is emphasized. According to the mechanisms of heat deposition in tissues by electromagnetic fields, which is discussed in (Plewako et al., 2003), when the tissue's electric dipoles (both permanent and induced) oscillate in response to the E-field of an applied wave, heat is generated by a process analogous to friction. When free charges (electrons and ions) in the tissue are set in motion by the E-field, collisions with immobile atoms and molecules in the tissue generate heat (Plewako et al., 2003). The propensity of the tissue to produce heat for a given sinusoidal E- field magnitude is determined by the values of the imaginary part of its relative permittivity ε" and its conductivity σ (Plewako et al., 2003). It is important that the internal E-field is responsible for the heat generation. In addition, the internal H-field is not directly responsible for heating because tissue has a permeability μ close to that of free space with no magnetic losses. But the time-varying H-field produces a resulting internal E-field and in this way it causes heating of tissue (Plewako et al., 2003).

Early age of hyperthermia procedure, three heating techniques are applied, which known as capacitive, inductive and radiative. They offer towards simplicity, insensitive with coupling condition and deep penetration, respectively. However, the main deficiency share by these 3 heating techniques, where the penetration depth and fields generated in the tissue are not optimum and this condition may affect other surrounding healthy tissue in negative ways. Currently, there are many types of applicators have been developed and investigated such as in (Choi, Lim, Yoon, & Member, 2016; Ovidio, Bucci, Crocco, Scapaticci, & Bellizzi, 2016)as to obtain the improvement in delivering heat into the targeted treated cancerous tissue. Varieties of results have been shown. Each of the paper aims in providing an improvement towards the investigated therapy through the use of electromagnetic fields, which then transferred in body into heat. Based on the previous works, electromagnetic hyperthermia deficiencies include the penetration depth, focusing, skin burns problem and difficult to control the required temperature for the procedure. Thus, the research is emphasized in determining the improving heating through the utilization of electromagnetic field, which produces by the antenna. The microstrip is selected to be used in this investigation. The microstrip can be developed with small size, lightweight and can be structured either in single or array. Furthermore, the characters of this antenna far outweighs of its limitations. The microstrip also has provided the utmost results towards hyperthermia cancer procedure as discussed in previous works (Drizdal, Togni, & Vrba, 2007; K. B. Lias, Ahmad Narihan, & Buniyamin, 2014; K. Lias & Buniyamin, 2013; Yin, Li, & Li, 2012). In hyperthermia for cancer procedure, the E field, which is produced by the microstrip patch is of prime consideration is transferred in the body into heat. Based on the bioelectromagnetism law (Jaakko Malmivuo & Robert Plonsey, 1995), the energy transferred from the magnet, B field through forces on permanent magnetic dipoles is not prominent in electromagnetic (EM) biological interaction, since most of the biological tissue is nonmagnetic, which means it is contains very few permanent magnetic dipoles.

Radiation is absorbed and distributed towards the cancerous tissue and measured by a measurement parameter known as the specific absorption rate (SAR). The SAR, which is provided in equation (1) is defined as transferred power as in equation (2) divided by the mass of the object. The unit for SAR is W/kg or mW/g.

$$SAR = \frac{\sigma}{2\rho}\left|E\right|^2 \quad \text{(W/kg or mW/g)} \tag{1}$$

With σ is the conductivity of tissue (S/m),   is an electric field (V/m), ρ is a density of tissue (kg/m^3).

$$P = \sigma E2 \quad \text{(W)} \tag{2}$$

The microstrip impacts towards the radiation absorption are observed for hyperthermia cancer procedure with breast is selected as the treated cancerous area.

RESEARCH METHODOLOGY

The research methodology is conducted with 3 main parts, which are the development of microstrip antenna or also called as a microstrip applicator in hyperthermia for cancer procedure, construction of breast phantom and water bolus, which is integrated in order to provide cooling environment onto the skin surface, where the heat is delivered. The microstrip applicator is developed with 2 different operating frequencies; 915MHz and 2450MHz, which contributes towards different sizes of the applicator. In order to construct the microstrip applicator, the length (L) and width (W) of the rectangular patch is first to be calculated by using the following equations (3) – (9).

$$w = \frac{c}{2f} x \sqrt{\frac{2}{\varepsilon r+1}} \quad (3)$$

where w is the patch antenna width, f is the operational frequency, εr is the substrate permittivity and c is the speed of electromagnetic (EM) wave in vacuum, which equal to 3X108ms-1.

$$\varepsilon eff = \frac{\varepsilon r+1}{2} + \frac{\varepsilon r-1}{2}\left|1+\frac{10h}{w}\right|^{-0.5} \quad (4)$$

where εeff is the effective permittivity of the microstrip line, h is the thickness of the substrate. The value of the characteristic impedance used mostly 50Ω and 75Ω. For this research, the 50Ω transmission line is used.

$$Leff = \frac{c}{2f\sqrt{\varepsilon eff}} \quad (5)$$

$$\Delta L = 0.412 X h X \frac{\varepsilon eff+0.3}{\varepsilon eff-0.258} X \frac{\frac{w}{h}+0.264}{\frac{w}{h}+0.8} \quad (6)$$

ΔL is used when considering the fringing effect, where Leff and εeff are changed. The fringing effect is resulted due to the propagating of EM wave at the outside of the patch.

$$L = Leff - 2\Delta L \quad (7)$$

$$Lg = 6h + L \quad (8)$$

$$Wg = 6h + w \quad (9)$$

The substrate used is FR-4 with 2mm thickness and εr = 4. Then, the breast phantom is constructed. The phantom breast tumour/cancer is positioned 100mm deep from the outer side of the breast skin. The radius for breast fat is 100mm, while the breast tumour phantom has a radius of 50mm. The electrical and thermal properties of the breast phantom are tabulated in Table 1. Last but not least is the development of water bolus, which is utilized in providing a cooling environment onto the skin surface of the heating area during hyperthermia procedure execution. Thickness of the water bolus may affect the shape and the effective field size (EFS) of the SAR distribution pattern (Jaakko Malmivuo & Robert Plonsey, 1995). Water bolus using distilled water as a coolant fluid with εr, σ and ρ are 76.7, 5e-005 and 1000, respectively. The illustration of the proposed hyperthermia design of simulation (DoS) for cancer procedure is provided in Figure 1. The FDTD package, SEMCAD X is used to carry out the simulation process in order to obtain the SAR distribution into the breast for hyperthermia procedure. SEMCAD X is a Speag product, which is affordable of toolsets for antenna design and general EM/Thermal simulation. Important theory behind FDTD is firstly proposed by Yee in the year of 1966 (Kulas & Mrozowski, 2011).

Table 1
Breast Phantom Electrical and Thermal Properties

			915MHz		
	Relative Permittivity, εr	Electrical Conductivity, σ (S/m)	Density, ρ(kg/m3)	Specific Heat Capacity, C (J/kg/K)	Thermal Conductivity, K (W/m/K)
Breast Fat	4.699	0.1251	1000	2348.33	0.209
Breast Cancer/ Breast Tumour	48.362	2.6531	1000	2352.55	0.789
			2450MHz		
Breast Fat	2.884	1.1179	1000	2348.33	0.209
Breast Cancer/ Breast Tumour	18.254	30.2181	1000	2352.55	0.789
Breast Fat	2.884	1.1179	1000	2348.33	0.209
Breast Cancer/ Breast Tumour	18.254	30.2181	1000	2352.55	0.789

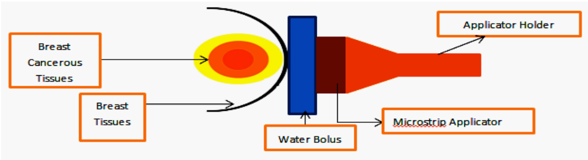


Figure 1. Illustration of the Proposed Applicator for Hyperthermia Cancer Procedure

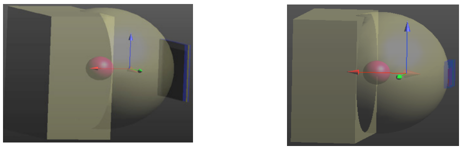
RESULT AND DISCUSSION

Based on the equations (3) – (9), the rectangular microstrip applicator specifications for 915MHz and 2450MHz are as tabulated in Table 2. The arrangement for the purpose of this simulation study is demonstrated in Figure 2. The EM simulation is conducted in order to obtain the S_{11}, E field and SAR distribution pattern. The S_{11} for 915MHz and 2450MHz are presented in Figure3, where it shows that the S_{11} for 915MHz and 2450MHz is around -13dB and -17dB, respectively. Based on the bioelectromagnetism interaction, the penetration of electromagnetic fields into biological tissues is decreased as frequency increases.

Table 2
Rectangular Microstrip Applicator Parameters

915MHz	2450MHz
Length (L) = 83mm	Length (L) = 30mm
Width (W) = 104mm	Width (W) = 39mm
Ground Length (Lg) = 95mm	Ground Length (Lg) = 44mm
Ground Width (Wg) = 118mm	Ground Width (Wg) = 51mm

The frequency and wavelength are related proportionally or asynchronously, while penetration depth and wavelength is synchronously related. The frequency-wavelength relationship is described in equation (10) and equation (11) presents the depth penetration-wavelength relationship.



(a) (b)

Figure 2. Full arrangement of hyperthermia for cancer procedure (a) 915MHz (b) 2450MHz

$$f = \frac{c}{\lambda} \quad (10)$$

Where f is frequency, c is the speed of light, $3.0X10^8$ ms^{-1} and λ is wavelength.

$$D = \frac{1}{2[\frac{2\pi}{\lambda}\sqrt{\varepsilon}\,(1+(\frac{\sigma}{\omega\varepsilon_0\varepsilon})^2)^{0.5}]} \quad (11)$$

Where λ is a wavelength, ε is a material permittivity, ε_0 is a permittivity of free space, σ is the conductivity of tissue (S/m), ω is an angle frequency.

The $[\frac{2\pi}{\lambda}\sqrt{\varepsilon}(1+(\frac{\sigma}{\omega\varepsilon_0\varepsilon})^2)^{0.5}]$ is known as absorption coefficient (α). By that, the equation (11) can be simplified to equation (12).

$$D = \frac{1}{2\alpha} \quad (12)$$

In Table 3, it is observed that electric field changes when the applicator distance is altered. The yellow colour represents the hottest temperature. When the distance is increased, the E field value is decreased. However, the E field distribution is insignificantly changed especially in term of the shape when the distance is increased. E field is transferred in the body into heat, which is the desired outcome of the hyperthermia procedure. When we observed from Table

3, the E field value is higher for 2450MHz than 915MHz. This is theoretically supported by the Planck-Einstein equation, equation (13).

$$E = hf = \frac{hc}{\lambda} \tag{13}$$

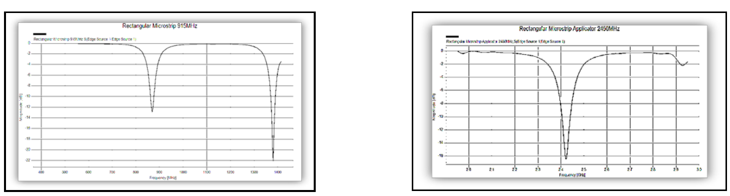
with $h = 6.62607004 \times 10 - 34\ m2\ kg\ /\ s$.

Also in equation (14), it is given that E field is concurrently related with frequency. This is called as the wave equation by Maxwell's, at position and time .

$$E(r,t) = E_0 cos(\omega t - kr + \phi_0) \tag{14}$$

With E_0 is constant vector, k is wave number and ϕ_0 is constant scalar. The angular

frequency, $\omega = 2\pi f$. Besides, the E field and SAR are also changed simultaneously, especially in term of the distribution pattern, which is described through equation (1). SAR is changed significantly with frequency. Nonetheless, the depth is satisfied for both frequencies with and without water bolus integration, which is up to 100mm. The depth is taken into consideration the brighter area, where the absorption is high. For 2450MHz, it is better in term of focusing capability if compared to 915MHz, where the unnecessary radiation area, which is at the vicinity breast area to be treated, is less.



(a) (b)

Figure 3. S_{11} for Rectangular Microstrip Applicator (a) 915MHz (b) 2450MHz

In addition, the SAR has varied depending on the conductivity of the material, σ. The higher the frequency contributes to higher σ. This is due to the part of loss caused by the motion of the bound charges as tissue with higher water content, such as muscle and breast tumour/cancer, is more lossy for a given E field magnitude than drier tissue as bone and fat.

The findings of this research are at par and even enhance in certain criteria such as the depth penetration and also the focusing capability, if compared to other research findings, which have been conducted previously, despite, with different design of simulation background environment. As for instance, 105mm and 60mm penetration depth were achieved with circular patch (Drizdal et al., 2007)and compact patch applicator (Ammann, Curto, Mcevoy, See, & Chen, 2009; Lim, Choi, Yoon, & Kim, 2015), respectively. On the other hand, when water

Table 3
E-field and SAR Distribution Pattern for 915 and 2450MHz

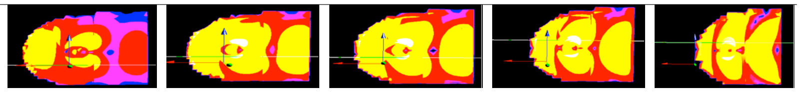
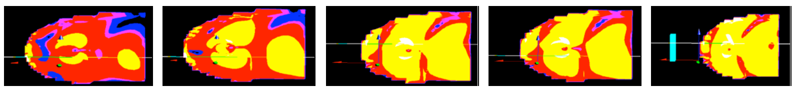
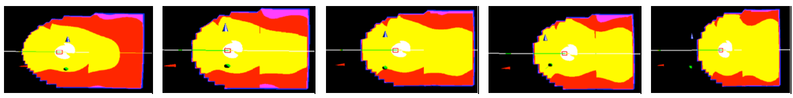
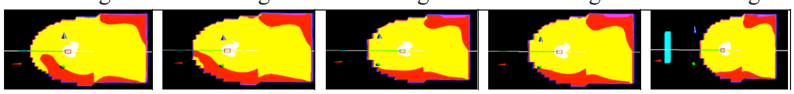
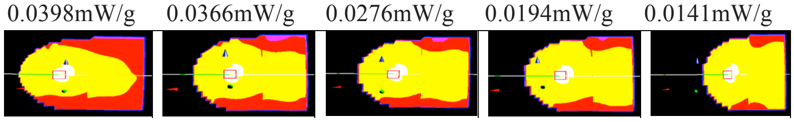
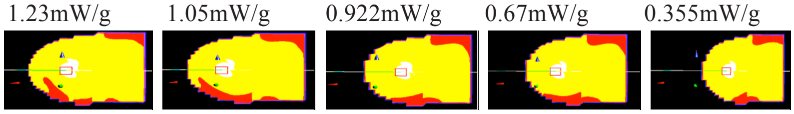
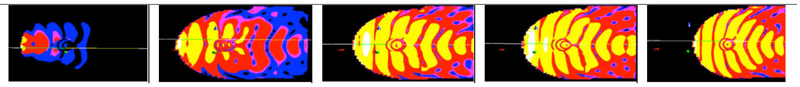
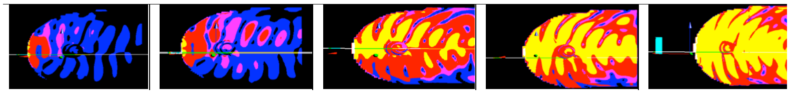
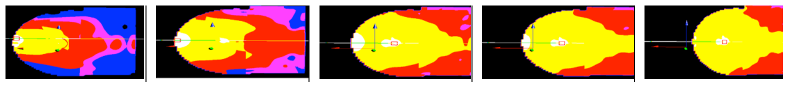
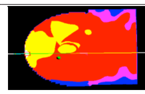
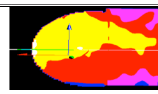
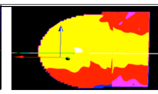
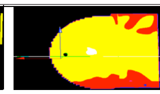
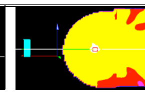
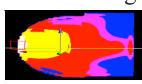
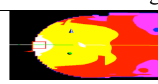
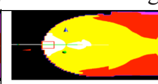
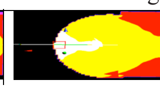
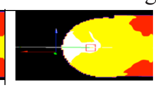
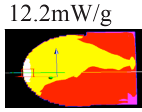
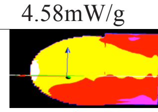
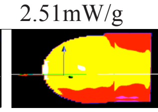
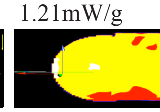
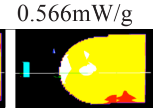
	Direct on the skin	20mm	40mm	60mm	100mm
	915MHz				
E field distribution without water bolus					
	300V/m	129V/m	123V/m	110V/m	8.78V/m
E field distribution with water bolus					
	71.8V/m	24.8V/m	19.7V/m	13.5V/m	8.78V/m
SAR 1g without water bolus					
	1.84mW/g	1.56mW/g	1.35mW/g	0.975mW/g	0.502mW/g
SAR 1g with water bolus					
	0.0398mW/g	0.0366mW/g	0.0276mW/g	0.0194mW/g	0.0141mW/g
SAR 10g without water bolus					
	1.23mW/g	1.05mW/g	0.922mW/g	0.67mW/g	0.355mW/g
SAR 10g with water bolus					
	0.0257mW/g	0.0242mW/g	0.0186mW/g	0.0133mW/g	0.00974mW/g
	2450MHz				
E field distribution without water bolus					
	2.97X103V/m	328V/m	181V/m	137V/m	113V/m
E field distribution with water bolus					
	159V/m	14.4V/m	7.92V/m	5.5V/m	4.12V/m
SAR 1g without water bolus					
	20.3mW/g	5.8mW/g	3.08mW/g	2.01mW/g	1.22mW/g

Table 3
E-field and SAR Distribution Pattern for 915 and 2450MHz (continue)

	2450MHz				
SAR 1g with water bolus					
	0.0803mW/g	0.00835mW/g	0.00304mW/g	0.00219mW/g	0.00158mW/g
SAR 10g without water bolus					
	12.2mW/g	4.58mW/g	2.51mW/g	1.21mW/g	0.566mW/g
SAR 10g with water bolus					
	0.0318mW/g	0.00616mW/g	0.00249mW/g	0.00136mW/g	0.00083mW/g

bolus is added, it is significantly observed that the E field and SAR distribution are changed in shape and depth. Hence, by adding the water bolus, it may reshape the effective field size (EFS), while keeping the vicinity of the targeted area cool during the execution of hyperthermia procedure, which also contributes towards minimal skin burn impact.

CONCLUSION

The simulation study on the SAR is conducted using the FDTD computational packages, SEMCAD X by Speag. Different operating frequencies are used to carry out the simulation study. Design of simulation (DoS) is provided in Figure 1. As observed from the results, different frequencies may provide satisfied depth, either with or without the integration of water bolus. Focus is better for 2450MHz. The integration of the water bolus assisted in providing the cooling environment on the vicinity of the targeted area during the hyperthermia procedure and help prevent skin burn. Furthermore, the water bolus also reshaping the E field and SAR contour and depth.

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