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PERFORMANCE EVALUATION OF COMPACT RECTANGULAR MICROSTRIP ANTENNA FOR BREAST HYPERTHERMIA

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Abstract- Many times, invasive cancer treatments are more painful than the disease. Even after treatment, the recovery rate and the survival of patients is another issue. The combinational therapy approach helped radiation oncologists for the effective and non-invasive treatment of cancer patients, where hyperthermia is used in combination with radiotherapy and or chemotherapy. Hyperthermia is the process of raising the temperature on the tumor site to more than 42 °C and healthy tissues at a safe limit for 20-60 minutes. Applicators for hyperthermia of breast tumors are heavy, bulky, and mainly operate at low frequency. In this article, a compact rectangular microstrip applicator for local hyperthermia of breast tumors is presented. The applicator is integrated with two different female breast models; a four-layer scattered fibro glandular breast model and a four-layer scattered fibro glandular breast model with water bolus (WB). The stage-II tumor of various sizes (10, 15, 20, 25, 30 mm^3) is inserted in both the breast models. The performance of the applicator is tested at various air gaps between the breast model and TSRMA. The SAR and temperature variations in healthy and tumor tissues are observed. The performance of the applicator is suitable and compatible with ISM band frequencies useful for breast hyperthermia.

Keywords: Breast Tumor, Hyperthermia Treatment (HT), SAR, Temperature, TSRMA.

1. INTRODUCTION

Cancer is a deadly disease; day by day, improvements in the field of non-invasive treatment modalities have shown their benefits in the survival rate of patients after the treatment. A recent database from GLOBCON shows that the rate of breast cancer has surpassed lung cancer and has a mortality rate of 11.7% [1]. So that research in the prevention of breast cancer, detection at early stages, minimally invasive treatment, fast recovery after treatment, and better life or survival after treatment is on the highest priority. Available and preferred treatments for cancer are surgery, chemotherapy, and radiotherapy.

Combinational therapy has become popular. Hyperthermia treatment helps to improve the effectiveness of chemotherapy (CT) and radiotherapy (RT). Hyperthermia is the process of raising the temperature on a tumor site more than 42 °C and healthy tissues at a safe limit for 20-60 minutes [2-4]. Due to such high-temperature heating, the tumor shrinks and becomes more sensitive to radiotherapy and chemotherapy. Controlled heating of breast tumor without hotspots on healthy tissues is a difficult task in breast HT.

In some cases, hotspots on healthy tissue occur due to overheating. Radiofrequency, microwaves, and ultrasound waves are used for HT. Low-frequency applicators (8 MHz-915 MHz) have proven their efficiency in HT of tumors at the human body's abdomen, head, and neck locations [5]. Many experimental validations and clinical trials have efficiently proven that microwave frequencies are best suited for breast HT [6-8]. Breast cancer generally happens in the size of 10-20 mm^2. In some cases, it is a recurrent type and develops superficially. These tumors can be treated with combinational therapy, HT and radiotherapy or chemotherapy.

Basic investigations about the location of the tumor in the breast and the patient's fitness are carried out for the application of HT. Biopsy and other techniques are used to find the stage of the tumor. This database is required for proper focusing of microwave power on the tumor site. The duration of HT depends on the tumor size, the patient's physical fitness, and tumor location. Generally, microwaves are preferred for breast tumor applications. Applicators reported in [9-17] are efficiently suits for superficial and deeply located tumors. They are bulky and requires more time for HT, so compact and efficient applicators are in demand. Coupling water bolus (WB) pads carrying deionized water between the surroundings of treatment region (breast skin) and applicator improves the performance of HT, reduces reflection and reduces hotspots on healthy tissue [18-19]. The flexibility of the applicator in terms of power, amplitude, phase, and position is additional merit of the compact applicator.

Simple settings of these parameters make an applicator widely suitable and acceptable for HT. Such simple and compact applicator can reduce the number of hotspots on healthy tissue. The concept of microstrip antenna came up around 1953-54, but the application based significant research and development initiated in 1970 [20], the feasibility of microstrip antenna for clinical applications is investigated [21], then integrated design and use of microstrip antennas for clinical applications started [21-23]. It is widely suitable for recent trends of ISM band applications [24].

In the article, a simple, compact and cost-effective teeth-shaped rectangular microstrip applicator (TSRMA) is designed and fabricated on an FR4 substrate. Two hemispherical breast models with a simple and WB are designed with a medical mammary radius of 80 mm. In every breast model tumor of different size has been embedded in CST-MW suite; four-layers (Skin, Fat, Gland, and Muscle) are considered in the design. These breast models are united with TSRMA in a simulation environment. The performance of TSRMA is evaluated in terms of SAR and temperature variations during the HT.

2. MATERIALS AND METHODS

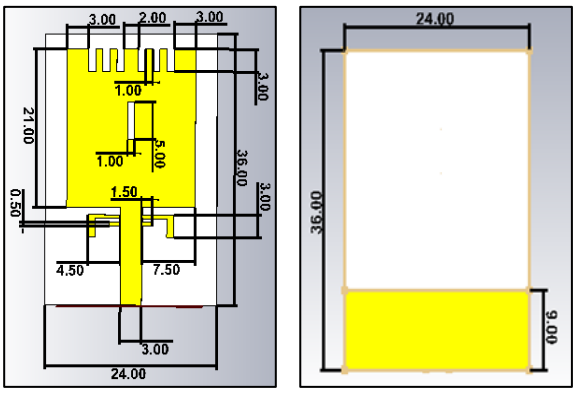
The design of the microstrip antenna, three-dimensional breast models, and bio-heat equations are discussed in this section.

2.1. Microstrip Antenna Design

A simple rectangular microstrip antenna is designed in the CST-MW suite and fabricated on FR4 substrate. Design parameters of TSRMA are mentioned in Table 1. The designed TSRMA and fabricated TSRMA are shown in Figures 1 and 2.

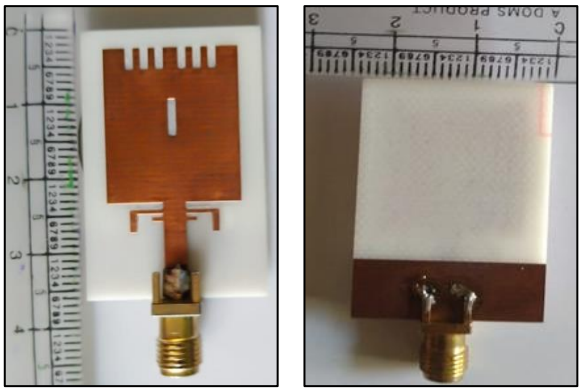
Table 1. Antenna design parameters

Parameter	Value
Relative permeability (μ_r)	1
Relative permittivity (ε_r)	4.4
Thickness of substrate (mm)	1.55
Thickness of copper-clad (microns)	25
Loss tangent (δ)	0.025



(a) top view (b) bottom view

Figure 1. Designed TSRMA



(a) top view (b) bottom view

Figure 2. Fabricated TSRMA

Figure 1(a) shows the patch layer and (b) shows the partial ground layer structure of the designed TSRMA. The fabricated structure is depicted in Figure 2(a), which shows the top layer and (b) shows the bottom layer. Dimensions of the antenna are designed and optimized using antenna design equations (1)-(5) taken from [25-28].

$$\varepsilon_{reff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[1 + 12\frac{h}{W}\right]^{-1/2} \quad (1)$$

$$L_{eff} = \frac{C}{2 f_r \sqrt{\varepsilon_{reff}}} \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} \quad (2)$$

$$W_{eff} = \frac{C}{2 f_r} \sqrt{\frac{2}{\varepsilon_{reff} + 1}} \quad (3)$$

$$F_{reff} = \frac{1}{2L\sqrt{\varepsilon_r}\sqrt{\mu_0 \varepsilon_0}} \quad (4)$$

$$W_f = \frac{7.48h}{e^{\left(\frac{z_o\sqrt{\varepsilon_r + 1.41}}{87}\right)}} - 1.25t \quad (5)$$

where, the effective dielectric constant and effective length of the patch is denoted by ε_{reff} and L_{eff}, Width of patch, height, and length is denoted by W, h, and L, C is velocity of light, f_r is resonant frequency, W_f is feed width, t is thickness of the strip line, and Z_o is output impedance.

2.2. 3D Breast Model Design

A four-layer scattered fibro glandular 3D female breast model of hemispherical shape, with a radius of 80 mm, is designed in the CST-MW suite depicted in Figure 3. The thermal and dielectric properties database is taken from the IT'IS foundation [29], and breast models based on [30] are used for realistic breast scenarios.

A similar model is designed with WB for performance evaluation with TSRMA in the CST-MW suite depicted in Figure 4. A stage-II tumor of various sizes (10, 15, 20, 25, 30 mm^3) is embedded in both breast models. The spatial location of the tumor is (10, 10, 45). For coupled simulation, breast models are integrated with TSRMA, 30 mm away from the apex point of 3D breast model. The breast model's thermal and dielectric characteristics are given in Table 2 [29], and tissue classification for the design of the breast model is shown in Table 3 [30].

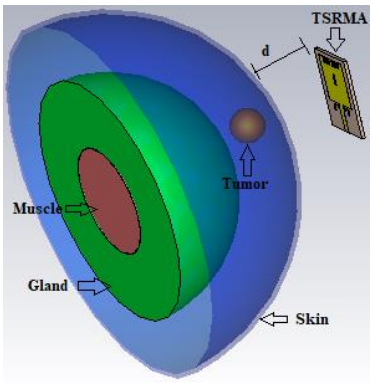


Figure 3. Four-layer breast model with TSRMA

Table 2. Breast Model Design Parameters at 2.76 GHz [27]

Tissue type	Relative Permittivity (f/m)	Electrical Conductivity (S/m)	Thermal Conductivity (W/m/°C)	Density (Kg/m^3)
Skin	37	1.62	0.37	1109
Fat	5.09	0.160	0.21	911
Gland	56.8	2.23	0.33	1041
Muscle	52.4	1.96	0.49	1190
Tumor	54.9	4	0.42	1058
Water bolus	83	1.72	0.60	994

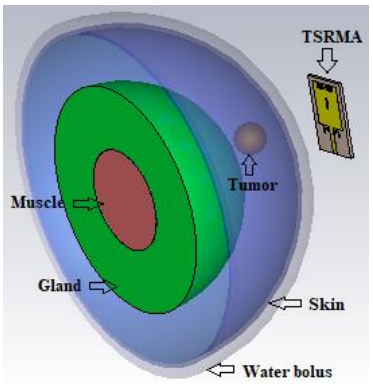


Figure 4. Four-layer breast model with TSRMA

Table 3. Breast Model Classification and Design Parameters [30]

Tissue type	Thickness of the tissue layer (mm)
Skin	02
Fat	14
Gland	40
Muscle	24
Tumor	10/15/20/25/30
Water bolus	05

Both the breast models are used with TSRMA in simulation, the performance of the TSRMA for different breast models is analyzed. SAR in tumor and temperature variations for different HT durations is analyzed in the electromagnetic (EM) and thermal simulation environment.

2.3. Hyperthermia and SAR

Tissue temperature is governed by Pennes bio-heat equation (6) is taken from [31], and the amount of heat absorbed in the breast tissue is measured by SAR given by equation (7) and taken from [32].

$$\rho.C\frac{\partial T}{\partial t}+\nabla.\left(-k\nabla T\right)=h_b\left(T_b-T\right)+\rho.SAR \tag{6}$$

$$SAR=\frac{\sigma}{2\rho}\left(\frac{d}{dt}\left|E_t\right|^2\right) \tag{7}$$

where, tissue characteristics are represented as ρ is density (kg/m^3), C is specific heat (J/mK), P is power dissipation, k is thermal conductivity (W/mK), T is temperature (°C). T_b is blood temperature (°C), h_b is convection heat transfer coefficient (Kg/m^3), σ is tissue conductivity (S/m), and E_t is electric field (V/m).

TSRMA is used to focus RF power (0.5 W) and uniform heating [30] on the tumor site in the simulation environment. In classical hyperthermia, the temperature on the tumor should be maintained between 42~45 °C (315.15~318.15 K) for damaging its protein structure. SAR and temperature variations in the breast tissue and tumor tissue were observed. We aim to focus MW power on tumor site [33], so according to the spatial location of the tumor, coordinates of the TSRMA are optimized for proper focusing on the tumor. Three coordinates - transformation of TSRMA concerning the top center of the breast model is performed as [(10, 5, 0)]. HT is applied for four cycles (0~20, 30, 40, 50 and 60 min).

3. RESULTS AND DISCUSSION

3.1. Simulated and Measured Antenna Parameters

Simulated parameters are obtained from the CST-MW suite, and measurements are carried on KEYSIGHT FieldFox Microwave Vector Network Analyzer (N9928A) are given in Table 4.

Table 4. TSRMA Parameters

Applicator	Resonant Frequency (f_1) GHz	Impedance Bandwidth & range (GHz)	Return loss
Simulated TSRMA	2.68	912 MHz (2.368 ~3.28)	-22.95 dB
Measured TSRMA	2.76	1.2 GHz (2.380 ~3.65)	-25.6 dB

A simulated and measured reflection coefficient plot of TSRMA for resonant frequency 2.76 GHz is illustrated in Figure 5, and VSWR is depicted in Figure 6. The lowest value of VSWR is (1.11).

3.2. SAR Analysis

Both the breast models are integrated with TSRMA for simulated SAR calculations. The SAR analysis is carried out for all tumor sizes. For the optimum performance evaluation, the distance between the TSRMA and breast model is varied. The performance is evaluated at an air gap of (d = 10, 20, 30 and 40 mm). SAR (1-g) profile summary of all tissues in HT for tumor T=15 mm^3 and distance d=30 mm is displayed in Figure 7. All healthy tissue is within the safe limit of exposure. Evaluated SAR for various tumors at different air gaps is mentioned in Table 5.

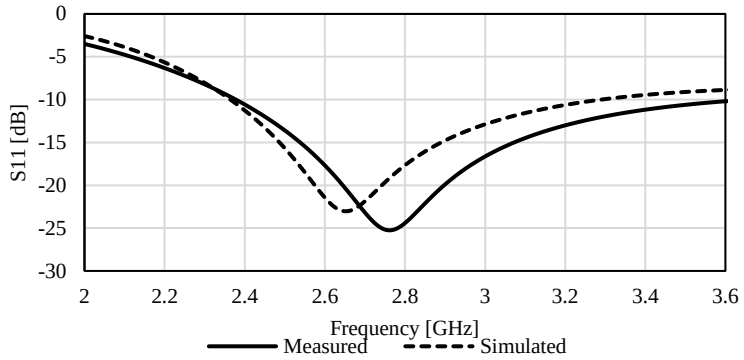


Figure 5. Variation in Reflection Coefficient v/s Frequency

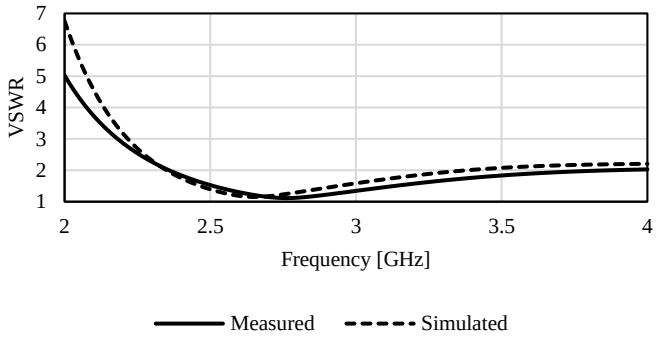


Figure 6. Variation in VSWR v/s Frequency

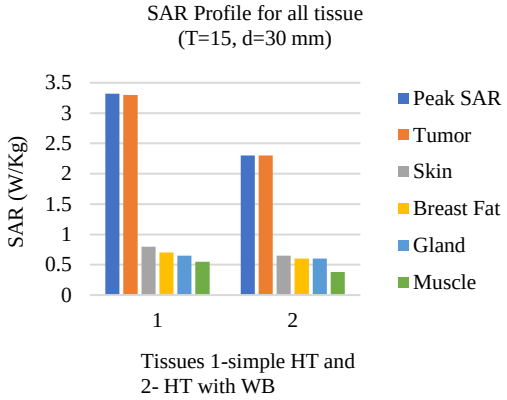


Figure 7. SAR profile for breast tissues (T=15 mm^3, d=30 mm)

The simulated SAR during the HT is observed in all tissues of the breast model. The performance of TSRMA is very good for tumor sizes of (10, 15 and 20 mm^3). The simulated SAR summary for all tumors at different air gaps (d) is shown in Figure 8. The SAR value decreases with an increase in the air gap (d). The evaluation observed that SAR is more for tumor sizes of 10, 15 and 20 mm^3. The performance of TSRMA for tumor sizes of 25 and 30 mm^3 is degraded. The patch size of TSRMA (18×24) limits its focus on the more extensive tumors. Increased patch size shall increase the size of the antenna. The required SAR value should not be less than 0.5 W/kg [34]. Such heating helps shrink the tumor, destroys its protein structure, and increases blood flow, making it highly responsive to chemotherapy and radiotherapy [2-5].

The WB is used to circulate thermally regulated deionized water. Due to this, hotspots are reduced, but SAR is also reduced. It prevents damage to skin tissues but adversely affects applicator radiations.

Table 5. SAR Analysis

Tumor size (mm^3)	Air gap (d= mm)	Breast model SAR 1-g (W/Kg)	Breast model with WB SAR 1-g (W/Kg)
10	10	14.8	10.63
	20	11.07	7.97
	30	3.5	2.52
	40	2.46	1.77
15	10	14.01	9.87
	20	10.5	7.5
	30	3.32	2.37
	40	2.33	1.66
20	10	12.99	9.07
	20	9.74	6.8
	30	3.08	2.15
	40	2.166	1.51
25	10	4.34	2.9
	20	3.25	1.46
	30	1.03	0.79
	40	0.72	0.41
30	10	3.71	1.77
	20	2.78	1.32
	30	0.88	0.42
	40	0.61	0.28

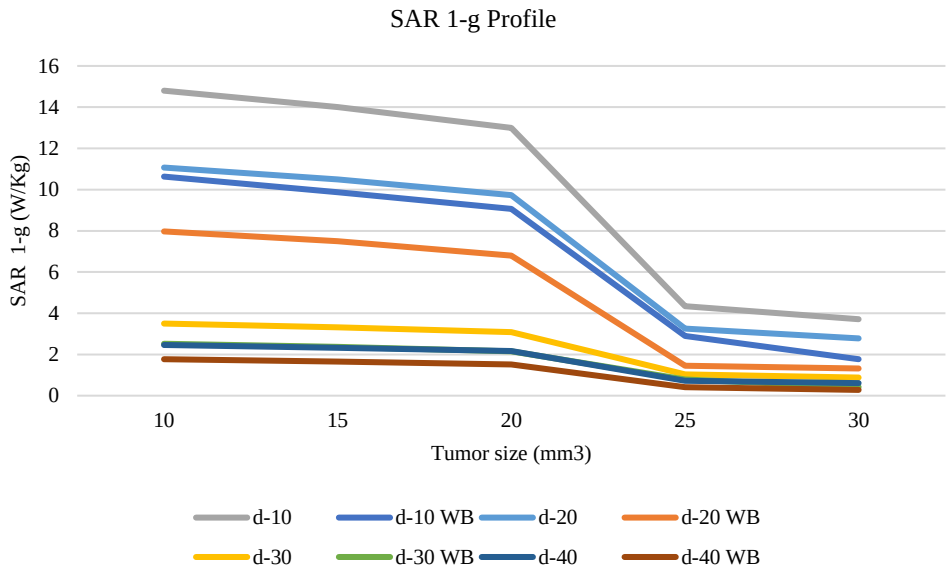


Figure 8. SAR 1-g profile for various tumor sizes and air gap (*d*) in mm

Negligible hotspots are observed on surrounding healthy tissue near the skin of the tumor. To enhance SAR and improve the performance of TSRMA with WB, a silicon layer can be used in the subsequent design and fabrication of the applicator [35].

3.3. Temperature Analysis

Thermal analysis is an essential part of the HT. Depending on the location, stage, and characteristics of tumor tissue, an appropriate temperature range can be selected. We have selected the temperature range 315.15-318.15 K, meaning 42-45 °C for the maximum treatment period of 0-60 min. A radiation oncologist can select the suitable duration of treatment, input power, and hyperthermia temperature range as necessary. The temperature analysis for the tumor (15 mm^3) is depicted in Figure 9. The heating of tumor is faster in HT of simple breast model. The desired temperature of 42-45 °C has been achieved in the treatment period of 30-50 min. Temperature is constant after -50 min. Due to this uneven heating of tumors, and some hotspots are observed on healthy tissue.

In comparison, it is slower in the HT of WB coupled model. The desired temperature of 42-45 °C has been achieved in 40-55 min. It is constant for up to 60 min. Uniform heating and reduction of hotspots are observed due to the coupling of the water bolus. The surrounding skin tissues are safe, and very few hotspots are observed on surrounding skin tissues of tumors. The water bolus coupling effectively controls hotspots and toxicity of breast HT [18-19]. Performance of TSRMA is compared with previously reported applicators of HT. It is described in Table 6. Their comparative parameters are taken from [9] and [10-17].

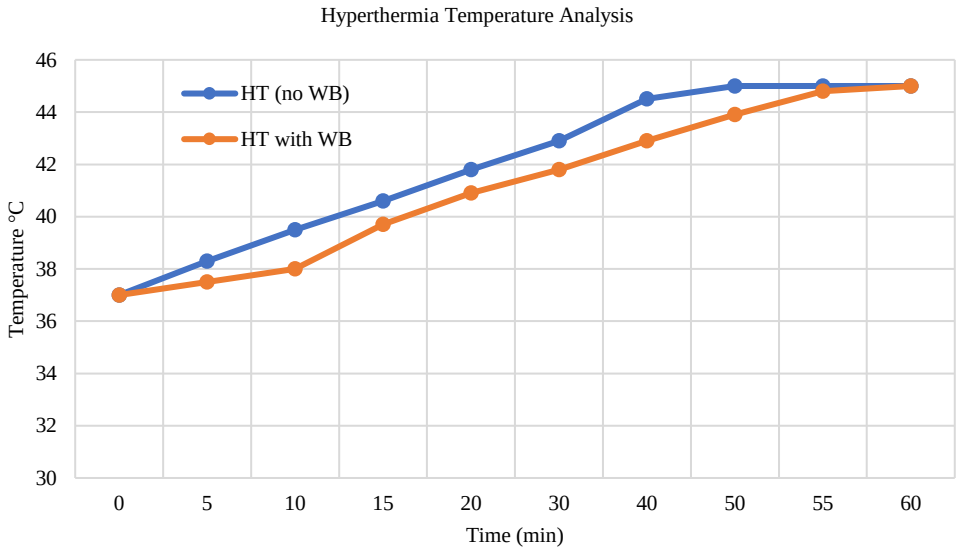


Figure 9. Temperature profile of Tumor (15 mm^3)

The applicators reported in Table 6 [9], [10-17] are low and high-frequency applicators, and their size is more significant than TSRMA. The proposed compact applicator can be used at MW frequencies with a robotic arm to achieve HT's better flexibility and comfort. Its performance can be improved by advanced combinational design with a silver layer and WB [35]. The obtained SAR in 1-g more suitable for HT applications recommended by the IEEE standards. The TSRMA has an advantage of compact size, variable input power and negligible hotspots are observed in HT.

4. CONCLUSION

In the article, we have simulated two breast models for different sizes of tumors. The first time we have proposed a compact applicator, and performance of the applicator was observed by integrating it with an entirely fat breast model and scattered fibro-glandular breast model.

For a similar distance (d) of 30 mm between the breast model and TSRMA, a breast model with WB has better results than a simple one. It reduces hotspots on surrounding healthy (skin) tissues and toxicity to a large extent. Simulated SAR and thermal analysis state that this compact TSRMA could be the candidate for robotic arm-based hyperthermia, where advanced temperature control and monitoring systems shall improve the complexity of HT. The heating of the tumor is uniform, and due to the compact size of TSRMA, it can be used in combination with WB. The TSRMA can be used for breast tumor treatment. Depending on the requirement, an appropriate SAR can be achieved by varying the distance between the breast model and TSRMA. For the higher performance of TSRMA, a silicon layer will be incorporated in the design of TSRMA.

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Table 6. Comparison of TSRMA with previous work [9] and [10-17]

Ref. Year	Frequency	Tissue type	Return Loss (dB)	Peak SAR (W/Kg)	Size (mm^2)
[9] 2017	f_1 = 434 MHz	3-layer	-16	1.32	124 × 124
[9] 2017	f_2 = 915 MHz	3-layer	-17	1.44	
[10] 2014	f_1 = 434 MHz	Tissue	-28	0.15	35 × 50
[10] 2014	f_2 =850 MHz	3-layer	-26	0.15	
[11] 2014	f_1 = 434 MHz	3-layer	-30	60	100 × 150
[12] 2012	f_1 =915 MHz	3-layer Tissue	-32	11.17	120 × 120
[12] 2012	f_2 =2.45 GHz	3-layer Tissue	-27	27.93	
[13] 2009	f_1 = 434 MHz	3-layer	-20	1.32	130 × 130
[14] 2008	f_1 = 434 MHz	3-layer	-19	20	78 × 78
[15] 2007	f_1 = 434 MHz	Tissue	-20.95	--	100 ×100
[16] 2019	f_1 = 2.45 GHz	Simple	-16.5	--	100 ×100
[17] 2020	f_1 = 2.45 GHz	Body phantom	20.95	3.69	170 × 250
This Work	f_1 = 2.76 GHz	4-layer skin, fat gland and muscle	-25.6	For *T*-10 mm^3 (d10)-14.8/10.63 (d20)-11.07/7.97 (d30)-3.5/2.52 (d40)-2.46/1.77 For *T*-15 mm^3 (d10)-14.01/9.87 (d20)-10.5/7.5 (d30)-3.32/2.37 (d40)-2.33/1.66 For *T*-20 mm^3 (d10)-12.99/9.07 (d20)-9.74/6.8 (d30)-3.08/2.15 (d40)-2.16/1.51 For *T*-25 mm^3 (d10)-4.34/2.9 (d20)-3.25/1.46 (d30)-1.03/0.79 (d40)-0.72/0.41 For *T*-30 mm^3 (d10)-3.71/1.77 (d20)-2.78/1.32 (d30)-0.88/0.42 (d40)-0.61/0.28	36 × 24

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