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Compact Conformal Multilayer Slot Antenna for Hyperthermia

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Abstract

A compact, conformal applicator having good impedance matching over various loaded conditions with minimum leakage radiation is desirable for hyperthermia treatment of cancer. Hence, in this paper, a new compact conformal multilayer slot antenna with embedded water bolus terminated in muscle medium is presented for hyperthermia application. A simple 50 Ω microstrip line with fork-shaped tuning stub is used to excite the proposed conformal antenna. The antenna input reflection coefficient and hyperthermia assurance parameters viz. effective field size, depth at $\Delta T/2$ and heating area in the tissue medium are evaluated for different antenna curvature at 2.45 GHz (curvature of the applicator is identical to the bio-model). The simulation results for the proposed antenna show a reduced tissue surface heating and back field irradiation.

1. Introduction

Hyperthermia is a therapeutic procedure used to raise the temperature of the cancerous region in the range 41 – 45 ºC [1]. Microwave hyperthermia can be delivered using an efficient conformal applicator explicitly designed to maintain the desired hyperthermia temperature range with minimal superficial heating. Typically, the performance of the applicator in close proximity to the tissue is very much influenced by the surrounding environment. Various forms of microstrip antennas at microwave frequencies have been investigated for hyperthermia application. However, the near-field for microstrip antenna is not symmetric which causes non-uniform field distribution [2]. The treatment performance can be improved by the use of a slot antenna and microstrip feedline which enhances the impedance bandwidth and effective field size (EFS) [3, 4].

For clinical applications, flexible applicators are usually bent around the patient's body with certain curvature. Changes in the applicator curvature due to bending might result in changes of heating pattern within the tissue [5]. Further, by employing a layer of water bolus as an interfacing medium between the antenna and tissue, cooling can be provided at the surface of the tissue along with better impedance matching between the antenna and tissue [6].

In this paper, a new compact conformal multilayer slot antenna with embedded water bolus, which is matched to the muscle phantom, is presented. The proposed antenna is more compact as compared to the slot and conventional patch antenna reported in reference [3-4]. Additionally, the reported applicator is perfectly flat [4] and the performance of the applicator is not studied in the presence of water bolus and bending situations. Hence, the bending effects of the proposed antenna with bio-model in the presence of water bolus are investigated on reflection coefficient, specific absorption rate (SAR) and temperature distributions. Simulation study is carried out using computer simulation technology microwave studio (CST MWS) 2017 software.

2. Applicator Design

The proposed antenna is a four-layer structure (Figure 1(a)) and it is comprised of: a high impedance superstrate (RT/duroid 6010) is used to avoid deviation in the effective permittivity of the muscle phantom and curvature around the antenna; a thin layer of double sided Rogers RO3003 substrate for printing the antenna; a neoprene layer to cover the back side of the antenna; a perfect electric conductor layer called back-shield to cover the back side of the neoprene surface.

The proposed antenna is a new compact microstrip slot antenna in which a circular corrugated conducting patch is enclosed within a corrugated circular slot. The corrugations in the circular slot of radius 6.8 mm and conducting patch of radius 4.5 mm on the ground plane of size 20 mm × 20 mm are done to miniaturize the proposed antenna. The corrugated circular slot is fed by a 50 Ω microstrip line with fork-shaped tuning stub printed on opposite side of the RO3003 substrate (ε_r = 3, tanδ = 0.001 and thickness = 0.787 mm). The optimized dimensions of the proposed conformal slot antenna are given in Figure 1(b). A superstrate layer of Rogers RT/duroid 6010 dielectric material having high dielectric constant (ε_r = 10.2, tanδ = 0.0023 and thickness = 1.27 mm) is placed over the antenna. The superstrate material having high dielectric value is employed in order to decouple the antenna from absorbing and lossy surrounding [7]. It is also used to avoid deviation in the effective permittivity of the tissue and curvature around the antenna. In order to restrict the back-field, which is harmful to the operator, a back-shield is used. A neoprene layer is inserted between the antenna and back-shield to maintain the impedance bandwidth. Further, water bolus is used to cool the tissue surface. The proposed applicator is designed at 2.45 GHz to effectively radiate into the tissue (ε_r = 50-j16) [3] which is in near field region of the antenna (Figure 1(d)) (unlike conventional antennas that are designed for free space radiations).

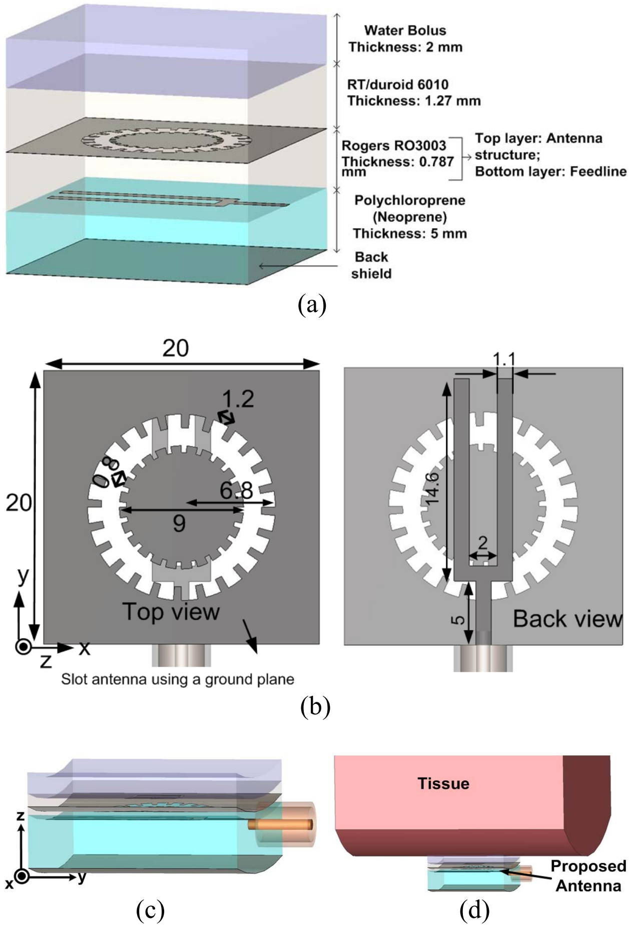

Figure 1. (a) Geometry of the proposed antenna, (b) The proposed multi-layer antenna structure, (c) The proposed antenna in bent condition, and (d) The proposed conformal antenna terminated in muscle medium.

3. Results and Discussions

The proposed conformal antenna is backed with neoprene and back-shield to suppress the back electric field associated with the proposed slot antenna. It is observed that significant amount of E-field is present in the absence of neoprene and back-shield. The back field associated with the antenna is undesirable and it would also be harmful to the operator. Hence, by using neoprene-back shield combination, the back radiation of the proposed antenna directed towards the tissue phantom (Figure 2).

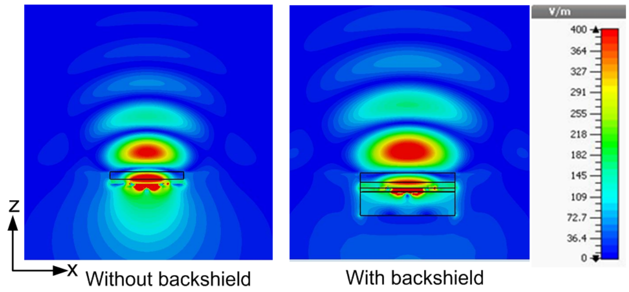

Figure 2. Near E-field distributions in xz-plane from the proposed antenna without/with backshield, radiating into the muscle medium.

In order to observe the effect of bending of the proposed applicator (Figure 1(c) and (d)) on input reflection coefficient, specific absorption rate (SAR) and temperature distributions, simulations were performed for five cases involving different values of system's radius of curvature 'R'. Case I pertains to both bio-model as well as the applicator having 'R' of 50 mm. Case II, III and IV represent 'R' of 100, 200 and 400 mm for the bio-model and the applicator while case V involves planar bio-model and the applicator with 'R' tending to ∞ (planar/flat).

3.1 EM Simulation Results

The variation of input reflection coefficient of the proposed antenna versus frequency was studied through simulation by taking radius of curvature 'R' of the system as a parameter. The simulation result for the proposed antenna is shown in Figure 3(a). Figure 3(a) illustrates that reflection coefficient of the proposed applicator remains sufficiently stable at 2.45 GHz (<-24 dB) for various values of system's radius of curvature.

To study the effect of change in the type of tissue medium i.e. in the dielectric constant of the medium on the reflection coefficient-frequency characteristic of the proposed applicator, simulations were carried out for a wide range of real part of relative permittivity (ε_r') of the tissue medium in the range 30 to 70, keeping the imaginary part of the relative permittivity of bio-model (= 16) unaltered. The reflection coefficient-frequency characteristic of the applicator shown in Figure 3(b) indicates that the impedance matching between the proposed applicator and tissue remains sufficiently stable when the real part of the relative permittivity ε_r' of the phantom is changed from 30 to 70. The proposed applicator's bandwidth is sufficient wide to endure such changes in the dielectric property of the tissue phantom.

The effects of variation in the system's radius of curvature on effective field size (EFS) are studied through EM simulation and the results are presented in Figure 4. Initially, power fed to the antenna is considered as 1 W in the simulation study. Simulated variations of EFS and EFS_{25} versus system's radius of curvature due to the proposed applicator are shown in Figure 4. EFS and EFS_{25} are defined as the area that is enclosed within 50% and

25% SAR contours respectively inside the muscle phantom. It is observed that the value of EFS and EFS_{25} in the tissue increases first and tend to saturate as system's radius of curvature is increased from 50 mm to ∞. Hence, it can be said that antenna-bio-model curvature has a marked effect on the value of EFS.

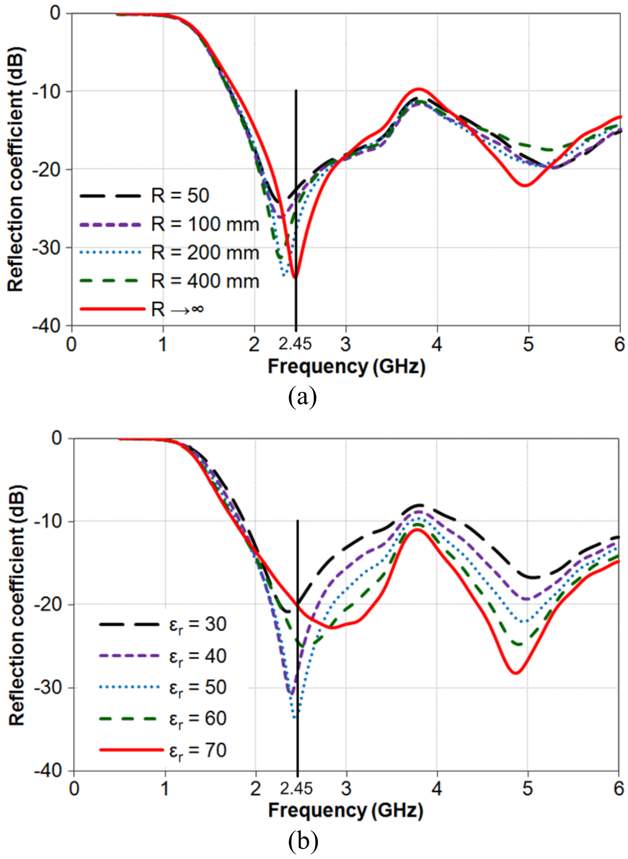

Figure 3. Variations of input reflection coefficient of the proposed antenna versus frequency for (a) different values of system's radius of curvature 'R' and (b) various dielectric constant values of the muscle phantom.

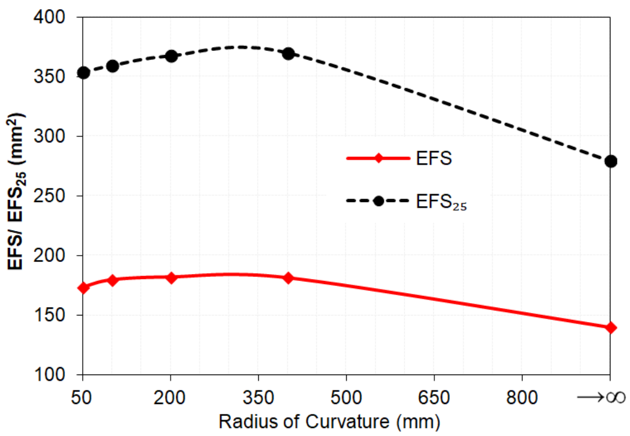

Figure 4. Variations of EFS/EFS_{25} with system's radius of curvature 'R' for the proposed antenna (at z = 10 mm in the muscle phantom).

3.2 Thermal Simulation Results

To characterize the hyperthermia treatment system, the proposed multilayer applicator was used in thermal simulation study to feed microwave power to the tissue for various curved surfaces as shown in Figure 1. CST multi-physics simulation software is used for thermal simulation at an initial tissue temperature of 37 ºC. It is worth mentioning that the value of heat transfer coefficient h of 100 $W/m^2/K$ and water bolus temperature of 30 ºC are taken up in the thermal simulation study [6]. The thermal parameters for the muscle tissue are same as given in [3].

The values of depth at $\Delta T/2$ and heating area as a function of various values of system's radius of curvature obtained through thermal simulation are illustrated in Figure 5. Heating depth at $\Delta T/2$ is defined as the depth at which temperature elevation reduces to half of the maximum with respect to initial temperature (= $\Delta T/2$) in the realistic tissue bio-model. Heating area is defined as the area where the temperature is in hyperthermia range (41-45 ºC) inside the muscle tissue. It can be depicted from Figure 5 that as the system's radius of curvature increases, depth at $\Delta T/2$ increases for fixed values of remaining parameters. Moreover, the heating area first increases and then reduces and approaches towards a saturation value with the increase in the system's radius of curvature (Figure 5).

The temperature distributions in the xz-plane for the bio-model with various curved surfaces are shown in Figure 6. It is clear that temperature distributions are symmetrical about z-axis and peak temperature in each case is aligned with the antenna's central axis of radiation. Further, the hot spot in the superficial region of the tissue surface is not observed for the system's radius of curvature considered in the study.

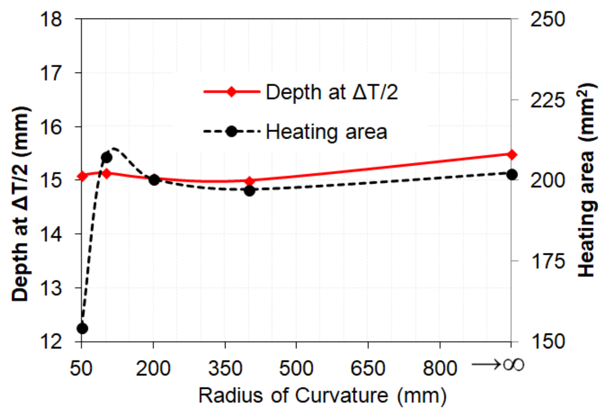

Figure 5. Variations of depth at $\Delta T/2$ (x = y = 0) heating area (at z = 10 mm in the muscle phantom) with system's radius of curvature 'R' for the proposed antenna.

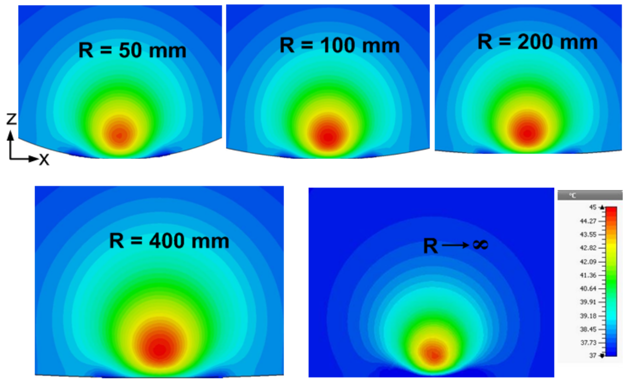

Figure 6. Simulated temperature distribution inside the muscle-model with various curved body.

4. Conlusion

The performance of a new compact conformal multi-layer slot antenna has been demonstrated through EM and thermal simulation for hyperthermia applications. The effects of change in the radius of curvature of the proposed antenna with bio-model on input reflection coefficient, SAR and temperature distributions in tissue are investigated through simulation. The results presented in this paper illustrate that it is very necessary to analyze the SAR and temperature distributions of hyperthermia applicators in both flat and bent (curve) state. The new proposed conformal antenna provides sufficient impedance matching in variably loaded conditions, with no hotspot at the superficial region of the tissue.

6. Acknowledgements

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7. References

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