Design of multi-element hyperthermia applicator using dielectric loaded folded dipole antenna

Baburam Mudavath and Kavitha Arunachalam
Department of Engineering Design, Indian Institute of Technology Madras, Chennai, Tamil Nadu, India

Abstract

Hyperthermia (HT), as an adjuvant therapy for cancer has been demonstrated to improve clinical outcomes. The efficacy of the treatment solely depends on device heating capabilities. Microwave tissue heating using multiple antennas is better suited for large solid tumors due to localized and selective power deposition. This is obtained by constructive interference of electromagnetic waves at the tumor site and destructive interference at the nontumor site. Antenna power deposition pattern and heating capabilities in tissues vary for different antenna designs. Here, we investigate the feasibility of using dielectric loaded folded dipole antenna for designing multi-element HT applicator (HA) using finite element method-based simulations at 434 MHz. A staggered array of folded dipoles is explored using time reversal technique for electronic steering of power deposition inside tissue at depth of 30 mm. The miniaturized antenna has good penetration depth of 2.4 cm, 77 MHz bandwidth, tissue specific absorption rate (SAR) of 18 W/kg with minimal healthy tissue hotspot. Preliminary simulation results at 434 MHz indicate that the miniaturized folded dipole antenna with dielectric loading could be used for HA design to treat oral cancer.

Keywords: cancer, folded dipole, hyperthermia, time reversal

1. Introduction

India has the largest oral cancer burden in the world. It is particularly diagnosed at locally advanced stage at which standard treatment modalities such as radiotherapy or chemotherapy has poor prognosis [1]. Many clinical trials have demonstrated that combining hyperthermia (HT) with radiation and/or chemotherapy enhances clinical outcomes [2]. HT treatment is a therapeutic process of selectively elevating tumour tissues to 40-44 ºC for a period of 60 minutes. This process induces cytotoxic effects in cancer cells and enhances their sensitivity to standard therapeutic interventions [3]. However, precise heat delivery to tumour target with minimal damage to healthy tissues has always been a challenge in HT. One of the most promising methods to achieve localized heating in HT is using microwave antenna array. The design of antenna element is the most vital aspect of a HT device and must fulfil multiple requirements such as small size, high penetration depth (PD), large effective field size (EFS), broad operational bandwidth with power reflection coefficient better than −10 dB, low mutual coupling with adjacent antenna elements, and high power handling capacity (up to 200 W) [4].

Microwave HT applicators (Has) emerged over the last two decades have employed waveguides, dielectric loaded horn, dipole and microstrip patch for tissue heating [5],[6],[7]. Wave guide and horn based applicators have better effective field size, penetration depth and specific absorption rate (SAR) than dipole ad microstrip patch designs, but have larger dimensions and weight. On the other hand, patch and dipole antenna based applicators are simple, conformal and light weight but have limited bandwidth and penetration depth. In this study, we would like to explore the feasibility of using dielectric loaded folded dipole antenna for designing a HA for treatment of oral cancer, which has not been reported in the literature.

Our objectives include, (a) design of a miniaturized single folded dipole antenna at 434 MHz and (b) design of conformal staggered antenna array to quantify the steering capabilities of the multi-element HA for treating oral cancer. Preliminary analysis is presented using three dimensional (3D) numerical simulations for a homogeneous tissue model mimicking the properties of bulk human head tissue. Electronic power steering capabilities of the dielectric loaded folded dipole antenna HA is analyzed using time reversal algorithm valid for homogeneous dielectric medium.

2. Methodology

2.1 Design of dielectric loaded folded dipole

The proposed antenna comprises of a gap fed folded dipole patch suspended at a height, h above 10 mm thick acrylic slab (150 × 150 × 10 mm^3) with rectangular ground plane as illustrated in Figure 1. The patch was modeled as a perfect electric conductor of width, $w = 2$ mm with long and short arms, L_1 and L_2, respectively. The distance between the two strips is L_3 and feed gap, g is 2 mm. The antenna was immersed in a rectangular deionized (DI) water bolus of size 150 × 150 × 25 mm^3. DI water enabled antenna size reduction, power coupling to lossy head tissue, and reduced tissue surface hot spots and antenna ohmic loss during heating. The 3D numerical model of the antenna shown in Figure 1 was enclosed in an air box. The external boundaries of the airbox were assigned as perfectly matched layers to absorb the outward radiated

EM fields. The dielectric properties used in the simulation is tabulated in Table 1. The simulations were carried out using ANSYS HFSS commercial software that solves the time harmonic vector wave equation [8],

$$\nabla \times \left(\nabla \times \vec{E}\right) - k_0^2 \varepsilon_r \vec{E} = -\mathrm{j}\omega\mu\vec{J} \qquad (1)$$

In Eqn. (1), k_0, ε_r and ω are wave number, dielectric constant and angular frequency, respectively, $\vec{J}$ is the impressed current density at the feed gap, and $\vec{E}$ is the electric field in the 3D computational domain. The antenna was excited using 50 Ω continuous wave source and design parameters, L_1, L_2, L_3, and h were determined using parametric sweeps to meet the following design criteria desirable for HT [9]: (i) resonance at 434 MHz with a greater than 90% power coupling to antenna ($|S_{11}|^2 \leq -10$ dB) (ii) 10 MHz bandwidth (−10 dB) and (iii) specific absorption rate (SAR) > 10 W/kg at 5 mm depth plane in tissue at 434 MHz. The tissue SAR was calculated from the computed electric field using the expression [9],

$$SAR = \frac{\sigma|\vec{E}|^2}{2\rho}, \qquad (2)$$

where σ [S/m] is the electrical conductivity of the tissue, and ρ [kg/m^3] is tissue mass density.

Table 1 Material properties used in simulation [9]

Material	Dielectric constant† (ε_r)	Conductivity† σ (S/m)	Density ρ (kg/m^3)
DI water	78.0	0.04	1000
Bulk tissue	56.0	0.83	1090
Aluminum	1.0	38×10^6	2689
PEC	1.0	1×10^{30}	1000
Acrylic	3.4	0	1000

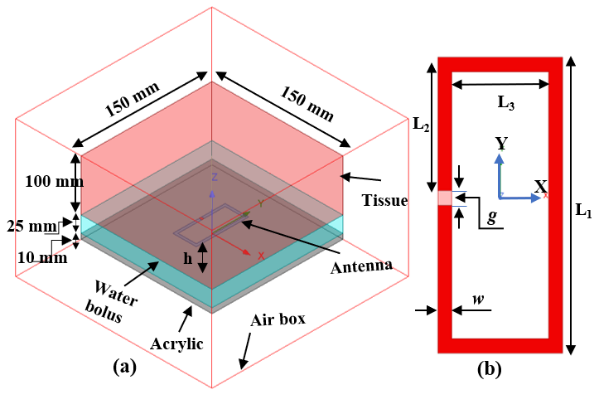

Figure 1 Numerical model. Single antenna simulation setup, (b) folded dipole antenna.

2.2 Staggered array design

A staggered array employing the optimized folded dipole was carried out for HT of oral cancer at maxillofacial site of human head as shown in Figure 2. The region of interest (ROI) in Figure 2(a) was chosen based on the location of the high incidence site for oral cancer. The outer skin contour was considered as the reference and 30 mm depth from this surface inside the human head was considered as the target plane, T_{XY} for steering the focus. A 25 mm extension of the skin surface away from the head was considered for designing the water bolus. The external surface of the water bolus was truncated as flat surface to define the 10 mm thick acrylic slab. At a height, h towards the head tissue from the inner surface of the acrylic slab, staggered array of antennas (A_1, A_2, A_3, A_4, and A_5) was defined inside the deionized water bolus as shown in Figure 2(b). Figure 2(c) shows the 3D numerical model used for array simulations.

Figure 3(a) shows the spatial arrangement of the staggered array elements with respect to the antenna local coordinate system denoted by C_1, C_2, C_3, C_4, and C_5. The array spacing s_x and s_y were optimized to reduce mutual coupling between array elements defined by the power transmission coefficient, $|S_{ij}|^2 \leq -10$ dB for $i \neq j$ and i, j = 1 to 5. The head model with properties of bulk head tissue was simulated with the array inside an airbox following the simulation methodology adopted in Section 2.1.

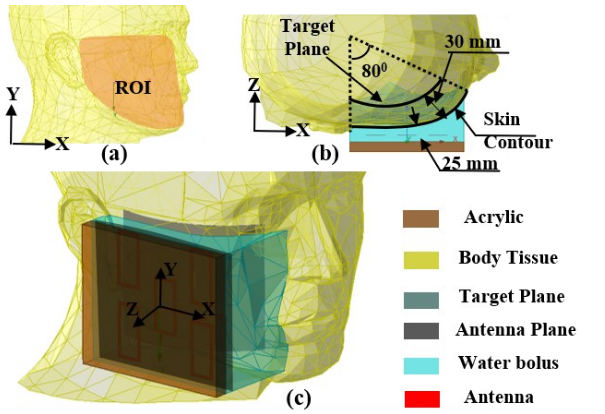

Figure 2 Staggered array design with 3D head model. (a) Region of interest (ROI) for oral cancer treatment, (b) cross sectional view indicating tumor target plane (T_{XY}) and arrangement of the staggered array, and (c) 3D view of simulation set up.

2.3 Power steering

Time reversal focusing method that is widely reported for wave propagation in homogeneous media was used to assess the power steering ability of the staggered array at the tumor target plane (30 mm depth). In this technique, virtual source is created at the desired focal point and response is recorded in each antenna element for virtual source excitation. The amplitude and phase of the electromagnetic (EM) field induced on the individual antenna for virtual source excitation is back-propagated after phase reversal for constructive interference at the focal point. The time reversal operation in frequency domain is given by [6].

$$P_c(f) = P_C^R(f)^* \qquad (3)$$

where P_c denotes the antenna steering parameters (power and phase), P_C^R is the complex phasor recorded by the array elements at excitation frequency, f and $*$ denotes complex conjugation operation. Three focal points (T_1, T_2, and T_3) were defined on tissue target plane, T_{XY} as shown in Figure 3(b). A virtual source was excited at a given focal point with 1 W at 434 MHz and steady state EM field induced at each antenna in the array were calculated. The recorded phasor amplitude was conjugated and magnitude was scaled such that the maximum input to each antenna is limited to 1 W. The focusing ability at the tissue target plane was quantified using *SAR* calculations for the time reversed excitation of the staggered array. Simulations were repeated for virtual source located at each focal point independently.

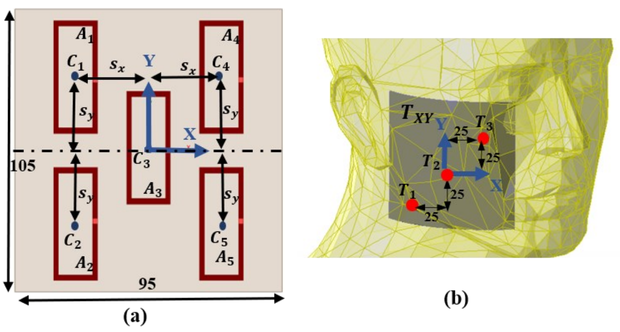

Figure 3 Array simulations. (a) Array spatial configuration, (b) virtual source representation at target plane (T_{XY}) inside the human head model for power steering.

4. Results and discussion

4.1 Single Antenna Analysis

Figure 4 shows the antenna resonance for the design parameters optimized using parametric sweeps. The optimized antenna parameters for 20 mm water thickness and 100 mm tissue load are, $L_1 = 40$ mm, $L_2 = 19$ mm, $L_3 = 18$ mm, $w = 2$ mm and $h = 6$ mm. The power reflection coefficient, $|S_{11}|^2$ at 434 MHz and −10 dB bandwidth are −37.89 dB and 77 MHz, respectively. Figure 4(b) show localized power deposition at 5 mm depth with *SAR* of 18 W/kg at 434 MHz. Simulation results of the dielectric loaded folded dipole show broad bandwidth and localized SAR which are desired for HT.

4.2 Array Antenna Analysis

Figure 5(a) shows the scattering parameters, $|S_{ij}|^2$ that summarizes the self and mutual power transmission capability of the staggered array for the optimal spacing of 25 mm along x and y axis in the local coordinate system, i.e., $s_x = s_y = 25$ mm. It can be observed that power reflection coefficient, $|S_{ii}|^2$ all antenna elements is below −10 dB which indicates more than 90% power coupling to the antenna elements. The mutual coupling defined by $|S_{ij}|^2$ for $i \neq j$ is also below −15 dB indicating less than 3.16% power coupling between array elements for the optimized array spacing. This indicates that the power fed to the array elements is primarily propagating towards the tissue.

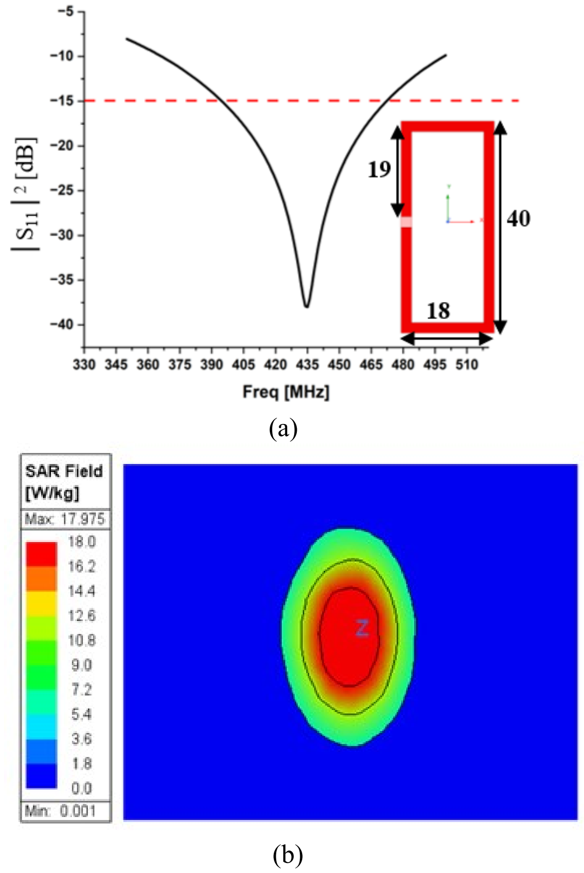

Figure 4 Single antenna simulation results. (a) Power reflection coefficient, $|S_{11}|^2$ and (b) tissue SAR at 5 mm depth in the target plane (T_{XY}).

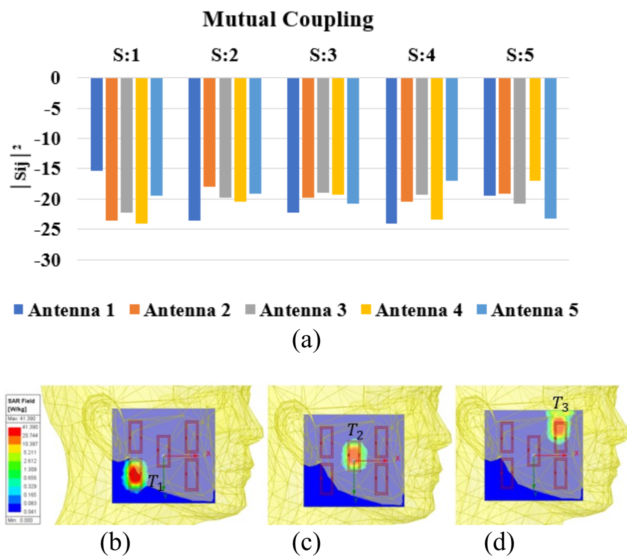

Figure 5 Array analysis at 434 MHz. (a) Array scattering parameters, $|S_{ij}|^2$ for the optimal spacing, power deposition at three focal points (b) T_1, (b) T_2, and (c) T_3 determined using time reversal.

Figures 5(b)-(c) show the time reversal simulation results of the optimized staggered array for the three focal points at the target plane. Array simulations indicate that the proposed staggered array is capable of steering and selectively depositing the power inside the tissue. Preliminary results obtained for homogeneous tissue model using time reversal method indicate that the miniaturized folded dipole antenna with dielectric loading could be used for HA design.

5. Conclusion

In this study, we reported numerical simulations of dielectric loaded folded dipole antenna for HT of oral cancer. A miniaturized folded dipole antenna operating at 434 MHz was presented. Numerical simulations were used to design a staggered array of folded dipoles for selective power deposition in a 3D human head model. Array performance was analyzed using time reversal method to assess the power steering capability at the ROI. The miniaturized antenna and proposed array configuration indicated selective power deposition in tissue and the ability to electronically steer the power in the target plane. It is concluded that the dielectric loaded folded dipole antenna could be used for designing HA applicator to treat oral cancer.

7. References

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