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Optimization of dual slot antenna using floating metallic sleeve for microwave ablation

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ABSTRACT

Backward heating reduction is vital in power distribution optimization in microwave thermal ablation. In this study, we optimized dual slot antenna to yield reduction in backward heating pattern along the antenna shaft with the application of floating metallic sleeve. Finite element methods were used to generate the electromagnetic (EM) field and thermal distribution in liver tissue. The position of the sleeve from the tip of the probe ($z = 0$ mm) was varied within the range $14 \le z \le 22$ mm while sleeve length was varied within $16 \le z \le 48$ mm at 2 mm interval using operating frequency of 2.45 GHz. The best optimized design has reflection coefficient of −20.87 dB and axial ratio of 0.41 when the sleeve position was at 17 mm and sleeve length was 18 mm. Experimental validation shows that inclusion of a floating metallic sleeve on dual slot antenna for hepatic microwave ablation averagely increased ablation diameter and aspect ratio by 17.8% and 33.9% respectively and decreased ablation length by 11.2%. Reduction in backward heating and increase in power deposition into liver tissue could be achieved by using this antenna to provide greater efficiency and localization of specific absorption rate in delivering microwave energy for hepatic ablation.

1. Introduction

Microwave (MW) coagulation therapy has drawn the attention of many researchers because of its medical applications in treatment of many types of cancers. Thermotherapy is a type of cancer treatment in which body tissue is exposed to cytotoxic temperature. Temperatures in excess of 60 °C are known to cause instantaneous death, while temperatures from 50 °C to 60 °C will induce coagulation by killing the cells and denaturing the protein structure within the cells. Thermal tumor ablation is becoming an alternative in the treatment of many types of cancers such as the lung, liver, bone, kidney and breast [1–3]. Many techniques are now in use to deliver heat to tissue, which include MW, radiofrequency, laser and high-intensity focused ultrasound. Each of these techniques is aimed at increasing heat to the tissue and raises the temperature to 50 °C and above in order to destroy cells within a localized region of tumor [4].

MW ablation is a form of dielectric heating where the dielectric material is the tissue. Dielectric heating occurs when an EM field is applied to an imperfect dielectric material. Heating occurs because EM field forces water molecules to oscillate. The bonded water molecules tend to oscillate out of phase with the applied fields; hence some of the EM energy is absorbed and converted to heat [3,5]. The rate of EM energy absorption will be high if the water content of the tissue is high (e.g. most solid organs), if low water content such as fat, less heating occurs. Tissue thermal conductivity (σ) and relative permittivity (ε_r) are other factors that can affect the EM absorption efficiency. At MW frequency typically 2.45 GHz, which is one of industrial, scientific and medical (ISM) dedicated frequencies, heating is more efficient in materials with high conductivity and permittivity [4,6].

Several antenna designs have been proposed to for effective treatment of tumors. These include monopole antenna, dipole antenna, slot antenna, tri-axial antenna, and cap-choked antenna [7–10]. Many of these antennas are not without drawbacks. For example, the specific absorption rate (SAR) distribution pattern of a monopole antenna is usually long, which results in backward heating along the antenna shaft. Dipole, slot, tri-axial, and cap-choked antennas have low power reflection coefficient but with significant backward heating and high dependence on insertion depth. Backward heating is one of the challenges of the proposed antenna designs as many researchers had shown that insertion depth effect on performance is minimal. Heating of antenna shaft can result from an impedance mismatch between the antenna and the surrounding tissue. Antenna

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characteristics relevant to thermal ablation include both the radiation distribution pattern and the reflection coefficient. In general, the lowest return loss is desirable to maximize energy transfer from antenna into the tissue [11–13]. Dual slot antenna has been reported to produce higher sphericity index than single slot antenna and others. Despite this advantage, slight SAR tail along the antenna is still conspicuous. The objective of this study is to design a dual slot antenna with floating metallic sleeve to reduce SAR tail (backward heating) to the barest minimum and to evaluate the effect of floating sleeve on the power reflection coefficient, SAR pattern and axial ratio.

EM modeling employs numerical methods to describe propagation of electromagnetic waves in biological tissues [14–17]. It involves the formulation of discrete solution using computationally efficient approximations to Maxwell's equations. Finite element method (FEM) has been extensively used to design and evaluate the EM radiation distribution patterns in the tissue. Other methods are the finite difference time domain (FDTD) which is based on Yee algorithm and the moment of method (MoM) for solving partial differential equations [14].

Computer models are a widely used tool in the design of antennas for microwave ablation (MWA) as they provide quick, convenient and accurate method of estimating antenna performance. A 2-D finite element method (FEM) is one of the numerical methods to determine the absorbed power, temperature profile, specific absorption rate (SAR) and reflection coefficient patterns in tissues.

In finite element method of modeling antenna for MWA, the electric and magnetic fields associated with the time varying transverse electromagnetic (TEM) wave, generated by the MW source propagating in a coaxial cable in the z-direction, was expressed in 2-D axially symmetric cylindrical coordinate. The use of FEM in designing of antenna for MW ablation has been extensively discussed in the literature [11–16]. The absorption of EM power in tissue is a function of dielectric permittivity, ε (F/m) and conductivity σ (S/m).

The specific absorption rate (SAR) pattern and frequency-dependent reflection coefficient in tissue are essential for the optimization of antenna for microwave ablation [13]. SAR represents the electromagnetic power deposited per unit mass in tissue (W/kg). The frequency, f, at which the power reflection coefficient is minimal, is called resonant frequency and it is the same as the operating frequency of the MW generator used. SAR pattern of an antenna causes temperature to rise but does not determine the final tissue temperature directly. Tissue temperature depends on both power and time. The most significant effect of an EM field applied to is the conversion of MW energy to thermal energy. The most widely used equation for modeling thermal therapy procedures is the Pennes' bioheat equation [18]:

$$\rho C_p \frac{dT}{dt} = \nabla \cdot k\nabla T + Q - Q_p + Q_m \tag{1}$$

where ρ is the tissue density (kg/m^3), C_p is the specific heat capacity at constant pressure (J/kg m^3), T is temperature (K), k is thermal conductivity (W/m K), Q is the absorbed EM energy [W/m^3]. Q_p is the heat loss due to blood perfusion (W/m^3) and Q_m is the metabolic heat generation (W/m^3). It should be noted that external heat source is equal to the resistive heat generated by the EM field.

Survival fraction of cells in tissue exposed to elevated temperature is given by [11]:

$$\Omega(t) = \ln\left[\frac{C(0)}{C(t)}\right] = \int_0^t A \exp\left\{-\frac{E_a}{RT(\tau)}\right\} dt \tag{2}$$

where $C(0)$ is the original concentration of undamaged cells prior to heating $C(t)$ is the concentration of undamaged cells after heating, Ω is a dimensionless damaged parameter. A (1/s) is frequency factor, E_a (J/mol) is the activation energy required to transform tissue from normal to damaged state, R (J/mol K) is the universal gas constant and

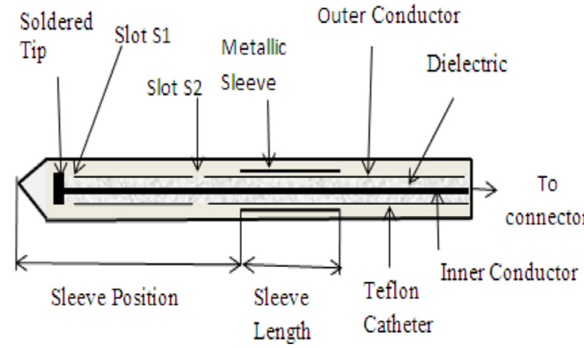

Fig. 1. Schematic of a dual slot antenna metallic sleeve for microwave ablation.

T (K) is the absolute temperature of tissue. Percentage of dead tissue, P, can be determined by using

$$P = 1 - e^{-\Omega} \tag{3}$$

From the above equation when $\Omega = 1$, there is 63% percent probability of cell death and when $\Omega = 4.6$, then the probability of cell death rises to 99%. The first case of $\Omega = 1$ corresponds to when tissue coagulation first occurs and tissue perfusion ceases.

2. Materials and methods

2.1. Computer simulation

The modeling of the antennas was based on the use of a 50 Ω UT-0.085′ semi-rigid coaxial cable. The inner conductor was made from silver-plated copper clad steel and the coaxial dielectric used is a low-loss solid polytetrafluoroethylene (PTFE). The outer conductor was copper; in which 2 slots, (S1 and S2) each of width 2 mm were cut to allow EM wave propagation into the tissue. The separation length between the two slots was 8 mm. In this study, the finite element (FE) package (COMSOL Multiphysics^{TM}, http://www.comsol.com) [15,16] was used to determine antenna efficiency and performance. This software allows us to specify the geometry of antenna, solves the Maxwell's equations and the heat equations in the surrounding tissues. The model involves the antenna inserted into large piece of liver. The dimensions of the antennas as well as designed variables are illustrated in Fig. 1. Two antennas were modeled: one without metallic sleeve and the second with metallic sleeve both of the same radius. In the first design, Teflon tape of permittivity 2.1 was used to wrap the outer conductor to a thickness of 0.65 mm. In the second phase of the optimization design, floating metallic sleeve made of copper (perfectly electric conductor (PEC)) was inserted. A Teflon catheter of 0.15 mm thickness was placed between the outer conductor and the floating sleeve, after which the antenna was in addition encased in a Teflon catheter to allow its easy removal from desiccated ablated tissue. The sleeve is electrically isolated from the outer conductor by using Teflon of thickness 0.15 mm. The sleeve position (sp) relative to slot S2 and sleeve length (sl) were adjusted on 121 simulated antennas. For this simulation, the probe tip was at $z = 0$ mm, the slots S1 and S2 were centered at $z = 5$ mm and 15 mm respectively. The sleeve position was in the range $16 \le z \le 22$ mm while sleeve length was within $16 \le z \le 48$ mm at 2 mm interval. The region of the simulated liver tissue was from $z = -10$ mm to $z = 80$ mm vertically and $r = 0$ to $r = 30$ mm horizontally. Variation of dielectric properties of tissue with temperature has been reported [11–13]. In this study we used average value of relative permittivity (43.03) and effective conductivity (1.69 S/m) as in Yang et al. and some other literature [20,22]. The dimensions and material properties of liver are represented in Table 1.