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Coaxial Slot Antenna Computer Modeling Design for Microwave Ablation in Breast Cancer

*Mario Candelario Cepeda Medina[1], Mario Francisco Jesús Cepeda Rubio[1],
Lorenzo Leija Salas[2] & Arturo Vera Hernández[2]

[1] Tecnológico Nacional de México/Instituto Tecnológico de la Laguna
[2] Sección de Bioelectrónica del Centro de Investigación y de Estudios Avanzados del IPN

ABSTRACT

With the improvements in imaging techniques that have allowed the earlier detection of smaller breast cancers, a number of minimally invasive techniques for the treatment of early stage breast cancers are being investigated. Ablative therapies, including laser ablation, focused ultrasound, microwave ablation (MWA), radiofrequency ablation, and cryoablation have been described. Microwaves applied to the tissue produce dielectric heat by stimulation of the water molecules within the tissue and the cells. The aim of this work is to compute the temperature distribution and the frequency-dependent reflection coefficient, when using a thin coaxial slot antenna in the breast tissue.

Keywords: Breast cancer, Microwave, Ablation

***Correspondence:**

M. C. Mario Candelario Cepeda Medina

Tecnológico Nacional de México/Instituto Tecnológico de la Laguna

Blvd. Revolución y Avenida Instituto Tecnologico de la Laguna Torreon, Coahuila, México 27000

mc33medina@yahoo.com.mx

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Introduction

In women, breast cancer is the most common incident form of cancer, followed by cancer of the lung, colorectal cancer and cancer of the corpus. Lung cancer is the commonest cause of cancer death in women, followed by breast cancer and colorectal cancer. Globally, breast cancer is the most common cancer among women, comprising 23% of all female cancers that are newly diagnosed in more than 1.1 million women each year. Over 411 000 deaths result from breast cancer annually, accounting for over 1.6% of female deaths from all causes [1].

The standard of care in the treatment of solid cancerous tumors is primary tumor resection. As in all surgery for breast cancer, the goal is to remove all of the cancer together with a sufficient margin of healthy tissue, to prevent local recurrence [2]. Recently, approaches other than traditional surgery has been explored, these techniques are minimally or totally noninvasive, and include, thermal energy us, microwaves, radiofrequency, interstitial laser photocoagulation, focused ultrasound, and cryotherapy. Microwave ablation (MWA), like Radiofrequency ablation (RFA), uses localized heating to cause tissue necrosis. Within the MW energy field, water molecules in the tissue rotate with the varying electric fields, causing frictional heating. This heating is determined mainly by power deposition in tissue, often expressed as specific absorption rate (SAR), but is also dependent on both the dielectric and thermal properties of the tissue being ablated. Lesion size is mainly limited by the available power and treatment time.

Furthermore, MW energy is promising because it can preferentially heat and damage high-water-content breast carcinomas, compared with the lesser degrees of heating that occur in lower-water-content adipose and breast glandular tissues [3]. Compared to RF, MW have a theoretically broader field of power density, with a correspondingly larger zone of active heating. This may allow for more uniform tumor kill both within a targeted zone and in perivascular tissue. Nevertheless, MWA has received less attention than RFA for breast cancer treatment.

In antenna design, computational electromagnetics (CEM), a discipline that employs numerical methods to describe propagation of electromagnetic waves, is broadly used to obtain numerical results for electromagnetic problems. Though there are various ways to classify the assortment of techniques in CEM, they are classified as either differential-equation-based or integral-equation-based. The finite-element method (FEM) is a technique that is differential-equation-based and can provide users with quick, accurate solutions to multiple systems of differential equations and as such, are well suited to heat transfer problems like ablation [4]. Numerous previous antennas design specifically targeted for cardiac and hepatic applications have been presented in the literature for MW ablation [5]. These designs have focused largely on thin, coaxial-based interstitial antennas, which are minimally invasive and capable of delivering a large amount of electromagnetic power. These antennas can usually be classified as one of three types (dipole, slot, or monopole) based on their physical features and radiative properties [6]. We have investigated the coaxial- slot antenna to apply to such a technique for breast cancer treatment. Research in thermal interstitial microwave ablation process in breast tissue using a coaxial slot antenna is not reported.

Materials and Methods

The frequency where the reflection coefficient is minimum is commonly referred to as the resonant frequency and should be approximately the same as the operating frequency of the generator used. Antennas operating with high reflection coefficients can cause overheating of the feedline possibly leading to damage to the coaxial line or due to the thin outer conductor damage to the tissue [7]. The behavior of interstitial antennas is evaluated by means of the reflection coefficient and the generated SAR pattern over the tissue [8,9]. However, microwave (MW) radiation and tissue thermal conduction cause the increase in tissue temperature. The Pennes Bioheat equation explains the thermal effects during the MWA. This equation explains the stationary heat transfer model presented by Equation (1)

$$\nabla \cdot (-k \nabla T) = \rho_b C_b \omega_b (T_b - T) + Q_{met} + Q_{ext} \tag{1}$$

where k is the tissue thermal conductivity (W/(mK)), ϱ_b represents the blood density (kg/m^3), C_b is the blood specific heat capacity (J/(kgK)), and ω_b symbolizes the blood perfusion rate (1/s). Additionally, Q_{met} and Q_{ext} are metabolism heat source and source of external heat (W/m^3), respectively. In these models, the metabolism heat source and perfusion were neglected because none of them are emulated in phantoms or in the computational model. The external heat source is equal to the resistive heat generated by the electromagnetic field. Dimensions and thermal properties for the materials and breast tissue are listed in Table 1, which were taken from the literature [10,11].

Table 1. Tissue and antenna parameters used in the finite element method (FEM) model.

Parameter	Value
Breast Electric Conductivity	0.14 S/m
Breast Relative Permittivity	5.14
Breast Thermal Conductivity	0.42 W/Mk
Breast Density	1020.00 Kg/m^3
Tumor Electric Conductivity	3.00 S/m
Tumor Relative Permittivity	57.00
Tumor Thermal Conductivity	0.50 W/mK
Tumor Density	1041.00 Kg/m^3
Blood Density	1000 Kg/m^3
Blood Specific Heat	3639 J/(Kg K)
Blood Perfusion Rate	0.0036 1/s
Blood Temperature	37ºC
Dielectric Relative Permittivity	2.03
Catheter Relative Permittivity	2.60
Microwave Frequency	2.45 GHz

Figure 1 shows the axial schematics of each section of the antenna, and the interior diameters.

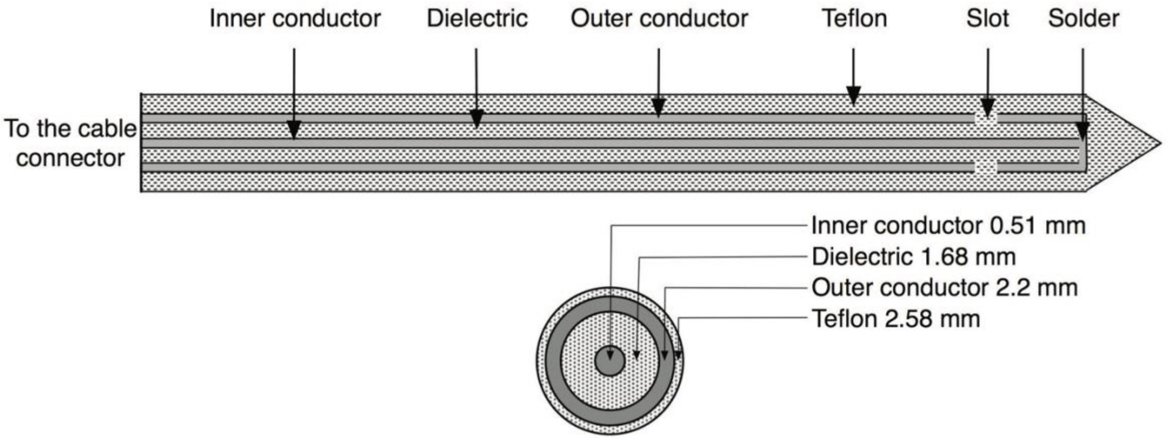

Figure 1. Cross section and axial schematic of the coaxial slot antenna.

Heating effects from the antenna during the thermal ablation process are modeled using commercial software package (COMSOL Multiphysics), which solves partial differential equations using the FEM. The coaxial slot antenna exhibits rotational symmetry around the longitudinal axis; therefore, we used an axisymmetric model [12], which minimized the computation time. The FEM model assumes that the coaxial slot antenna is immersed in homogeneous breast tissue. The inner and outer conductors of the antenna were modeled using perfect electric conductor boundary conditions and boundaries along the z axis are set with axial symmetry.

Results

Figure 2 shows the geometry of the antenna model. The finite element mesh, presented in Figure 3 has been selected in order to achieve a compromise between accuracy of computation and reasonable dimensionality of the model. Dense mesh zone has been generated in the vicinity of the tip of the antenna, where the temperature is more concentrated [13].

This mesh consists of 3627 triangular elements. Figure 4 shows the temperature distribution. The simulated reflection coefficient expressed logarithmically of the double slot antenna at the commonly used MWA frequency 2.45 GHz is - 3.2.

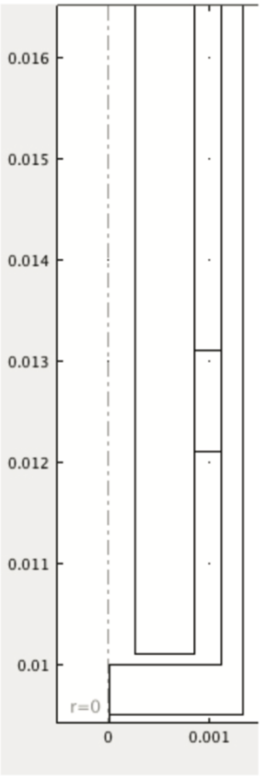

Figure 2. Axisymmetric CEM model in the vicinity of the tip of the coaxial slot antenna.

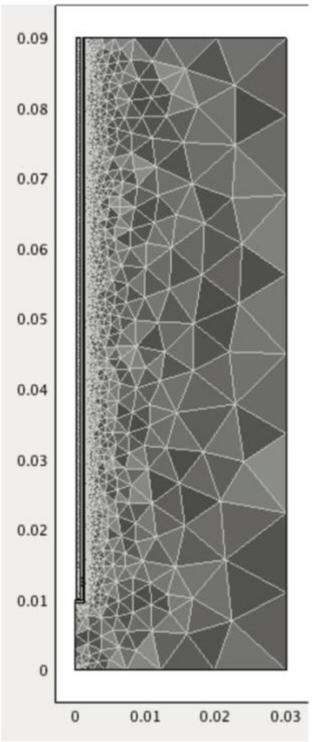

Figure 3. The electromagnetic model with mesh grids.

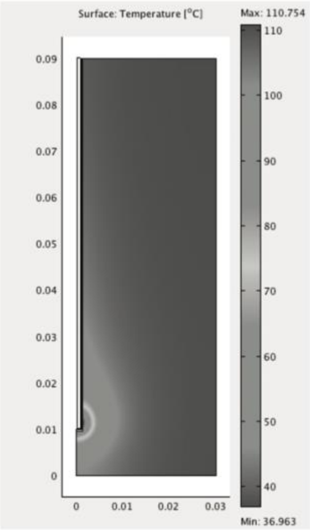

Figure 4. Temperature distribution.

Discussion

An antenna for MWA was simulated using an axisymmetric electromagnetic model. Once the theoretical model has been built, and although it is based on equations which correspond to well characterized phenomena, the next step is the experimental validation conducted to guarantee the results obtained from computer simulation.

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