In Silico Coaxial Antenna Design Applicator Optimization for Microwave Ablation Therapy in Medium Adipose Tissue Density Breast with Ductal Carcinoma *In-Situ*

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Abstract. Since 2020, breast cancer has been the one with greater incidence across the world. It is important to evaluate the possibility of the application of this minimally invasive procedure to treat the different types of premalignant lesions present in this type of cancer. Since microwave ablation therapy has been proven effective against liver and bone cancer, this research aims to assess the feasibility of an optimization method for the design of an antenna applicator that takes into consideration the effective wavelength of the breast tissue. Therefore, the computational finite element method is used to evaluate the therapy in an *in-silico* environment, which considers the thermodynamic, dielectric properties of the materials, modelling the response of the heat transfer in biological tissues due to microwave and the matching of the antenna. Achieving a $S_{11} = -24.79$ dB, SAR = 25 dB, and maximum temperature of 110 °C for a medium fat tissue density breast model. Inserting a 14 mm of diameter sphere with the characteristics of Ductal Carcinoma In-Situ, resulted in a $S_{11} = -11.47$ dB. Thus, not only maintaining the desired values for the coupling parameters, but also reaching greater ablation zones and temperatures with the lesion.

Keywords: Microwave Ablation · Standing Wave Ratio · Power Reflection

1 Introduction

Microwave ablation (MWA) therapy has been proven a reliable and effective treatment for bone and liver cancer [1, 2]. During MWA therapy, the antenna applicator is guided to the target tissue percutaneously with the guidance of computerized tomography, ultrasound, or magnetic resonance imaging. High-frequency electromagnetic waves are radiated into the tissue in which the antenna is inserted, which causes tissue death due to the coagulation and protein denaturation caused by the heating effect of microwaves to the

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polar molecules present in the tissue [3]. Many optimization methods have been used to obtain large and round ablation zones in this type of cancers [4–6], but few have been applied to breast cancer MWA therapy [7]. Since 2020 breast cancer has been the type of cancer with greater incidence and mortality across the world [8], it is important to evaluate the possibility of the application of this minimally invasive procedure to these types of lesions. However, since the dielectric properties in the breast tissue varies with the fat density, it is important to evaluate the feasibility of MWA in different types of fat tissue densities. Hence, this paper aims to assess the possibility of an optimization method that takes into consideration the effective wavelength of breast tissue with medium adipose density tissue.

2 Materials and Methods

2.1 Bioheat Transfer Due to Electromagnetic Waves

MWA is achieved thanks to the interaction of the electromagnetic waves with the polar molecules of the biological tissue [9], this interaction produces movement, therefore friction and heat are generated [10]. This heat is transferred across the tissue and is described by the *Pennes* Bioheat Equation, shown in Eq. (1). It takes into consideration the thermodynamic characteristics of blood in the perfused tissue. Were, ρ_{bl} is the blood density, C_{bl} is the blood-specific heat capacity, ω_{bl} is the blood perfusion rate, T_{bl} is the blood temperature, ρ is the tissue density, C is the tissue-specific heat capacity, k is the tissue thermal conductivity, T is the final temperature.

$$\frac{\rho C \partial \mathrm{T}}{\partial \mathrm{t}} = \nabla \cdot (\mathrm{k} \nabla \mathrm{T}) \rho_{\mathrm{bl}} \mathrm{C}_{\mathrm{bl}} \omega_{\mathrm{bl}} (\mathrm{T}_{\mathrm{bl}} - \mathrm{T}) + \mathrm{Q}_{\mathrm{met}} + \mathrm{Q}_{\mathrm{ext}} \tag{1}$$

The term Q_{met} is the metabolic activity, which is minimal during the therapy, therefore its neglected from the computational analysis. The external heat produced by the antenna applicator is described by the term Q_{ext}, which is proportional to the conductivity of the tissue and the electric field, described as follows:

$$\mathrm{Q}_{\mathrm{ext}} = \sigma E^2 \tag{2}$$

To evaluate the efficiency of the power delivered to the tissue with the antenna, several parameters need to be considered. Such as the frequency dependent coefficient (S_{11}). Which requires the input power and reflected power [11], hence:

$$\mathrm{S}_{11} = 20 \log_{10} \Gamma = 10 \log_{10} \left(\frac{\mathrm{P_r}}{\mathrm{P_{in}}} \right) (\mathrm{dB}) \tag{3}$$

where the Γ term enables the calculation of the *Standing Wave Ratio* (SWR). This parameter allows us to determine the mismatch of the antenna, thus:

$$\mathrm{SWR} = \frac{1 + |\Gamma|}{1 - |\Gamma|} \tag{4}$$

Γ is useful to calculate the percentage of reflected power to the source of the microwaves, obtained with the following equation:

$$\%\ \mathrm{P_r} = 100\,|\Gamma|^2(\%\ ) \tag{5}$$

The *specific absorption rate* (SAR) represents the amount of power deposited per unit mass, which depends on the tissue conductivity σ, the electric field E, and the density of the tissue ρ:

$$\mathrm{SAR} = \frac{\sigma}{2\rho}\left|\vec{\mathrm{E}}\right|^2\left(\mathrm{W}\cdot\mathrm{Kg}^{-1}\right), \tag{6}$$

This parameter defines the absorption of microwave energy, which causes temperature to rise, however, it does not determine the temperature distribution in the tissue. At last, the geometric parameters for the antenna applicator design are given by the effective wavelength of the breast tissue, given by:

$$\lambda_{eff} = \frac{c}{f\sqrt{\epsilon_r\mu_r}} \tag{7}$$

where c is the speed of light, f is the operating frequency, ϵ_r is the relative permittivity of the breast tissue, and μ_r is the relative permeability of the medium.

2.2 Model Definition

The physics behind the *Pennes* bioheat equation and electromagnetic waves is described by systems of partial differential equations that can be modeled and solved by numerical methods and computational means. One such numerical method is the *Finite Element Method* (FEM), that aims to solve the physics involved in the given dimensional model (which can be 1D, 2D, 2D-Axi-Simetric or 3D) by dividing the geometry into simple elements. Thus, by applying this discretization solving the system of equations at the nodes of edges of each element. For this study, we use *COMSOL Multiphysics 5.5* software to apply a parametric sweep, frequency domain, and time dependent studies to our breast model with medium fat tissue density. The model solution took 34 min, a 6 core i7-8750H Intel CPU 32 GB of DDR4 RAM Laptop was used for the simulations.

The breast model tissue proposed is a semi-sphere of a 72 *mm* radius, as seen on Fig. 1. For the study simulations we need to consider the dielectric and thermodynamic characteristics of breast tissue, that's why Table 1 shows these parameters for a breast with a medium adipose tissue density. Specifically, we feed the tissue Cole-Cole parameters to a modified Debye expression to get the relative permittivity and conductivity of a breast with medium fat density [12].

Equation (7) was the foundation for the maximum element size for the model mesh, taking into consideration the effective wavelength of the intermediate fat density tissue, which resulted in 879013 domain elements, 128478 boundary elements, and 7709 edge elements. For electromagnetic wave physics, we chose the external domains of the breast and antenna as the scattering boundary condition. The boundary condition for the bioheat transfer is the thermal insulation in the external boundaries of the geometries.

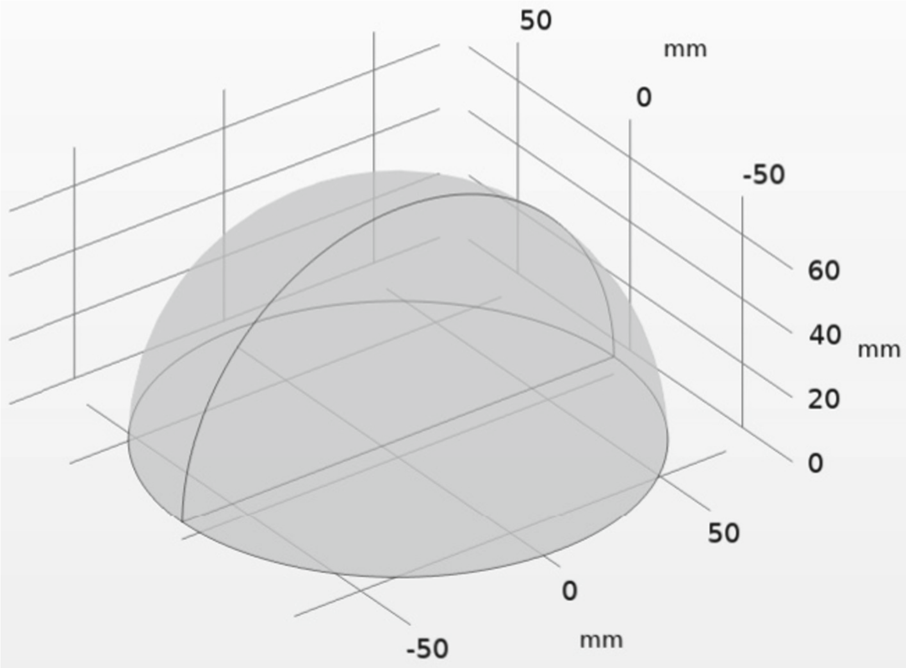

Fig. 1. Breast Model

Table 1. Thermodynamic and Dielectric Parameters of the Proposed Breast Tissue.

Parameter	Magnitude	Unit	Reference
Density ρ	932	$kg \cdot m^{-3}$	[12]
Thermal Conductivity K	0.171	$W \cdot m^{-1} \cdot K^{-1}$	
Heat Capacity at Constant Pressure C	2,200	$J \cdot mol^{-1} \cdot K^{-1}$	
Relative Permeability μ_r	1	–	[13]
Relative Permittivity ϵ_r	23.5959	–	
Electrical Conductivity σ_s	0.5	$S \cdot m^{-1}$	
Blood Density ρ_{bl}	1040	$kg \cdot m^{-3}$	[14]
Blood Specific Heat C_{bl}	3,639	$J \cdot Kg^{-1} \cdot K^{-1}$	
Blood Perfusion Rate ω_{bl}	0.0036	s^{-1}	

For the antenna applicator we propose an original 3D model of a double slot coaxial antenna that is comprised of an outer and inner conductors made of copper and an internal dielectric made of PTFE (As seen in Fig. 2), where the UT-47 coaxial cable standard is used. The geometric and dielectric parameters are shown in Table 2.

Table 2. UT-047 antenna parameters.

Parameter	Magnitude	Unit	Reference
Internal Conductor Diameter	0.287	*mm*	–
External Conductor Diameter	1.19		
Internal Dielectric Diameter	0.94		
Relative Permittivity of Copper	1	–	[13]
Relative Permittivity of PTFE	2.03		
Electrical Conductivity of Copper	5.998×10^{7}	$\mathrm{S} \cdot \mathrm{m}^{-1}$	
Electrical Conductivity of PTFE	5.1×10^{-17}		

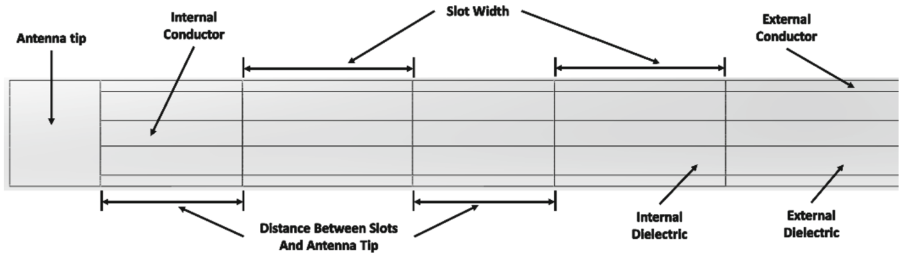

Fig. 2. UT-047 coaxial double slot antenna model.

2.3 Effective Wavelength (λ_{eff}) Driven Optimization

The proposed optimization method is based on the effective wavelength of the breast tissue, as seen in Eq. (7), which relays on the relative permittivity of the medium density of adipose tissue (MD) ϵ_r, the operating frequency $f = 2.45$ GHz, with an arbitrary power of 8 W, and the speed of light $c = 3 \times 10^{8}$ m/s. Given the relative permittivity of the MD breast, the calculated $\lambda_{\mathrm{eff}} \approx 25$ mm, therefore, we propose rational multiples of λ_{eff}, as seen in Table 3, for the Slot Width (SW) and Distance Between Slots (DBS) parameters of the antenna.

Table 3. Slot Width and Distance Between Slots Parameter definition based on λ_{eff}

Parameter	λ_{eff} rational multiples			
Slot Width	$\frac{\lambda_{\mathrm{eff}}}{4}$	$\frac{3 \cdot \lambda_{\mathrm{eff}}}{16}$	$\frac{\lambda_{\mathrm{eff}}}{8}$	$\frac{\lambda_{\mathrm{eff}}}{16}$
	6.2500 mm	4.6875 mm	3.1250 mm	1.5625 mm
Distance Between Slots	$\frac{\lambda_{\mathrm{eff}}}{10}$	$\frac{3 \cdot \lambda_{\mathrm{eff}}}{40}$	$\frac{\lambda_{\mathrm{eff}}}{20}$	$\frac{\lambda_{\mathrm{eff}}}{40}$
	2.50 mm	1.875 mm	1.250 mm	0.625 mm

3 Results

The optimization of the SW and the DBS was done by applying a parametric sweep through all the rational multiples of the calculated effective wavelength given in Table 3. The goal is to find the SW and DBS that achieve de desired values of $S_{11} \leq -10\,dB$, $\%P_r \leq 10\%$, and $SWR \leq 2$ [15, 16]. Therefore, Table 4 shows the combination of values for the SW and the DBS, where with a $SW = 1.875\,mm$ and a $DBS = 1.5652\,mm$ the better parameters are obtained, achieving values for $S_{11} = -24.79\,dB$, $\%P_r = 0.36\%$, and $SWR = 1.1286$.

Table 4. Combination of SW and DBS values with the desired values for s_{11}, SWR, and % P_r.

SW (mm)	DBS (mm)	SWR (Eq. (4))	S_{11}dB (Eq. (3))	%Pr (Eq. (5))
0.625	3.125	1.3986	−15.589	2.76%
1.25	1.5652	1.1799	−21.666	0.68%
1.25	3.125	1.7807	−11.033	7.88%
1.875	**1.5652**	**1.1286**	**−24.379**	**0.36%**
2.5	1.5652	1.439	−14.895	3.24%

With the parameters that yielded the best results, we evaluated thermal performance by modelling a 520 s MWA therapy in the proposed MD breast tissue, as seen in Fig. 3. Notice that the greater concentration of power given by the normalized SAR distribution, in Fig. 3a, corresponds with the heat distribution seen in Fig. 3b.

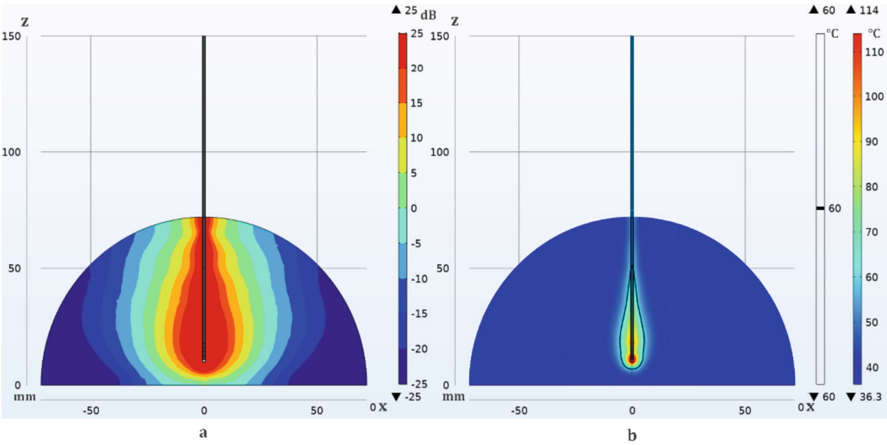

Fig. 3. Normalized SAR and temperature distribution in MD breast tissue.

With these results, the MWA therapy was also applied to a sphere that stands as a *Ductal Carcinoma In-Situ* (DCIS) mass of 14 mm of diameter, to know the thermal characteristics and the coupling of the antenna with a malignant tissue. Where the thermal and dielectric parameters of the DCIS lesion are taken from [17], thus, resulting in a $S_{11} = -11.47dB$, $SWR = 1.7198$, and a $\%P_r = 7.004\%$. Where it is clearly seen in Fig. 4, that the energy is more concentrated within the DCIS boundaries, thus achieving more heat in the lesion.

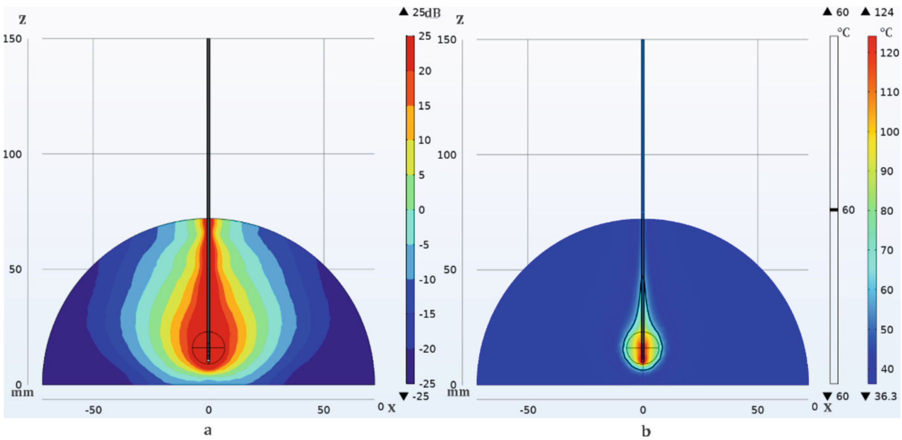

Fig. 4. Normalized SAR and temperature distribution in MD breast tissue with DCIS.

4 Discussion

This computational optimization has achieved the main goal of an antenna design capable of having the desired coupling parameters for matching the applicator with a breast tissue with medium fat tissue density, making this study relevant, as previous works [17–19] only dealt with a breast with high adipose tissue density, which does not represent the entirety of patients who could experience these conditions. The tissue irreversible damage starts at 45 °C, but it is best to achieve temperatures between 50 °C and 100 °C [20]. Therefore, the desired ablation temperatures are reached in the $520\,s \approx 8.66\,min$ therapy time, shown in Fig. 5, which also shows that the antenna worked within its operational 150 °C temperature.

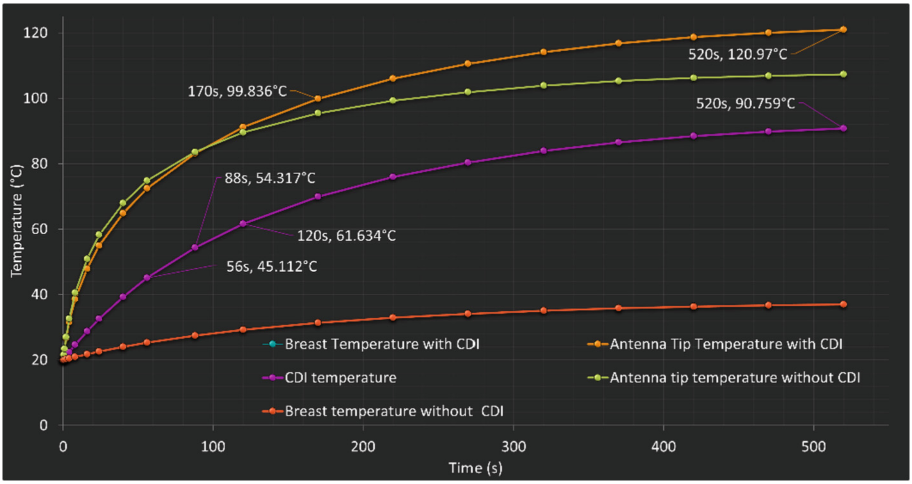

Fig. 5. Average temperatures reached over a 520 s MWA therapy time within the breast tissue models, antenna tip and DCIS.

5 Conclusions

The presented computational optimization successfully achieved the desired coupling parameters, $S_{11} = -11.47dB$ which represents a $\%P_r = 7.004\%$, for effective microwave ablation therapy in breast tissue. The proposed antenna design demonstrated efficient energy delivery and temperature control, resulting in targeted and controlled thermal treatment, because the ablation temperature of 55 °C is reached on the tumor domain before 100 s and can be sustained for at least 20 s before reaching temperatures that might compromise the proper functioning of the antenna, as seen in Fig. 5. Since this can be obtained with 8 watts of power, it is not necessary to simulate other power conditions. Moreover, since blood perfusion is not considered in this model, it is expected that the temperature distribution due to this factor will be more efficient, allowing for a longer duration of the ablation treatment. Comparing this study with those previously conducted, it can be observed that the breast's adipose tissue density is crucial for optimization and proper treatment planning. This approach holds promise for potential application in breast cancer treatment, warranting further exploration and validation through experimental studies.

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