Investigation of Influence of Coaxial Antenna Slot Positioning on Thermal Efficiency in Microwave Ablation using COMSOL

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Abstract
Continued development of the minimum invasive interventional technology in recent years has proven ablation therapy to be a safe and effective local treatment for cancers and has become increasingly important in the medicine field. This is the reason for its preference for treating larger tumors ahead of radiofrequency ablation. The authors numerically studied the influence of the geometry of the antenna used on the efficiency of the procedure to obtain a thermal lesion at the site of the tumor by varying the distance from the position of the end of the antenna with COMSOL Multiphysics as the modeling tool. The coaxial antenna investigated has a 1.79 mm diameter range with a center conductor of 0.29 mm diameter and Tefzel ETFE as the material of the catheter. The power of the coaxial antenna was optimized with a slot spacing of 6 mm from the tip of the antenna. The total power dissipation density, and thus the degree of thermal damage generated during the process was found to depend on the position of the slots of the coaxial antenna.

Keywords: Coaxial antenna, Microwave ablation, Thermal lesion and Tumour.

1. Introduction
Cancer can be described as a compound disorder that can be attributed to an environmental phenomenon [1]. In recent years, ablation therapy has been proven to be a safe and effective local treatment for cancers and has become increasingly important in the continuing development of the minimally invasive interventional technology [2]. In the treatment of kidney cancer, the rate of morbidity and complications in thermal ablation is lower than that in partial nephrectomy, however, the cancer specific mortality rate remains a major benefit of nephrectomy [3]. Ablation, a minimally invasive procedure, is now commonly used to treat small tumors of human organs extending from the liver, kidneys, pancreas and even the heart, particularly in cases where surgery is not a good option. Ablation is best for tumor sizes less than 7 cm and optimal results with tumor sizes of about 3 cm [2,3]. While microwave ablation (MWA) and radiofrequency ablation (RFA) are commonly used heat ablation techniques, ethanol ablation and cryotherapy are gaining importance. Microwave ablation (MWA) and radiofrequency ablation (RFA) provide necrosis using thermal energy developed by the probe used in one of three methods. by surgery, percutaneously or laparoscopically by image guidance. While microwave ablation uses high frequency microwaves to cause thermal damage, high frequency ablation uses high frequency alternating current to cause damage [4,5]. Ethanol ablation causes necrosis by direct injection of concentrated alcohol against the application of heat. It is normally used only when the tumors are
very small and contaminate other treatment techniques such as hepatocellular cancer, while the cryotherapy reaches a very low temperature by the passage of cold gases through the probe to the site of the tumor and is effective at larger tumor sizes than other ablation techniques [6,7].

The reduced dependence of microwave ablation on the electrical conductivity of the tissue and its reliability at higher tumor temperatures make it a more effective method of treating tumors larger than the radiofrequency ablation procedure [8-11]. The offer of hope for patients who cannot stand the operation, combined with a reduction in the recovery time, cost and potential of multiple tumor sites of renal ablation by microwaves has made this method an alternative to partial nephrectomy [12-19]. Improved image guidance technology has also made microwave ablation safer and more effective in the treatment of kidney tumors [20,21]. Microwave ablation therapy is less procedurally painful than other ablation techniques and also offers the benefits of elevated tumor temperatures and shorter ablation time [22,23]. It typically uses electromagnetic radiation at frequencies of either 915 MHz or 2.45 GHz to provide thermal damage to the tumor [24-27]. The propagation of microwaves determines the degree of thermal injury caused during microwave ablation. This is related to the intensity, the duration, the geometry of the antenna and the relative permittivity of the tissue [28-30].

Different types of antenna geometry have been studied, such as the coaxial base and sleeve, and the geometry is minimally invasive and efficiency has been found to be a function of the Specific Absorption Ratio (SAR) [31-36]. In addition to the antenna geometry, the material properties of the catheter also contribute to the degree of necrosis that can be achieved during microwave ablation [37]. This study deals with the distribution of the antenna temperature as a function of slot position during microwave ablation, tissue necrosis being dependent on the ambient temperature. Temperatures above 42°C are generally considered lethal to human cells [35, 37].

2. Methodology
The digital model follows the COMSOL Multiphysics based microwave cancer therapy for coaxial slot antenna geometry. Radiofrequency and heat transfer modules were used to model the area of liver ablation caused by the antenna. The catheter material used for this work was Tefzel ETFE, based on earlier findings that it has properties that promote a higher level of thermal lesion [35]. The geometry of the modeled antenna is shown in Figure 1.

![Figure 1. Coaxial antenna geometry](image-url)
The inside of the metal scale is not modeled while the metal parts are modeled using constraints by setting the tangential component of the electric field to zero. For the operation of the antenna a frequency of 2.45 GHz, and a temperature of 37°C was used to simulate the state of body fluids. Numerical modeling was performed in a two-dimensional axisymmetric coordinate, using rotational symmetry of the problem. The equations governing the propagation of electromagnetic waves in coaxial cable and characterized by transverse electromagnetic fields are as follows:

\[ E_z = \varepsilon_0 \frac{c}{\mu} \phi/(\omega t - kz) \]  
\[ H_z = \varepsilon_0 \frac{c}{\mu} \phi/(\omega t - kz) \]  
And
\[ Z = \varepsilon_0 \frac{c}{\mu} \frac{r_{\text{in}}}{r_{\text{out}}} I_n \left( \frac{r_{\text{in}}}{r_{\text{out}}} \right) \]

where \( r_{\text{in}} \) is the inner radius of dielectric material, \( r_{\text{out}} \) is the outer radius of dielectric material, \( Z \) is the impedance of the dielectric wave, \( \omega \) is the angular frequency, \( P_{\text{ab}} \) is the power input, while, \( r, \varphi, \) and \( z \) are the cylindrical coordinates. The wave number which is the propagation constant \( k \), 
\[ k = \frac{2\pi}{\lambda}, \]
and since \( V = f_\lambda \) and \( \omega = 2\pi f \), therefore, the propagation constant expressed as a function of the wavelength (medium) as;

\[ k = \frac{2\pi}{\lambda}, \]

Using a weakly reflective boundary condition, the antenna is modeled using the axially symmetric transverse magnetic formulation because the electric field in the tissue has a finite axial component and the magnetic field is purely in the azimuthal direction.

\[ n\sqrt{\varepsilon} E - \sqrt{\mu} H_g = -2\sqrt{\mu} H_g \]

The bio-heat equation determines the heat transfer as a function of time and neglects the heat of the metabolism.

\[ \rho C_p \frac{\partial T}{\partial t} + \nabla \cdot (-k \nabla T) = \rho b l d C_{b l d} \omega b l d (T_{b l d} - T) + Q_{\text{ext}}, \]

where \( T_{b l d} \) is the temperature of blood, \( \omega b l d \) is the blood perfusion rate, \( k \) is the thermal conductivity of tissue, \( Q_{\text{ext}} \) is the external heat source which is equal to the resistive heat generated by the electromagnetic field, \( C_{b l d} \) is blood specific heat capacity, and \( \rho b l d \) is the blood density.

The necrotic tissue fraction is derived from the expression;

\[ \Phi_\text{d} = 1 - \exp(-\alpha), \]

where the tissue injury degree \( \alpha \) is based on the Arrhenius equation;

\[ \frac{dE}{dt} = F_t \exp \left( \frac{-dE}{RT} \right), \]

\( F_t \) is the frequency factor, \( dE \) is the activation energy of the irreversible damage.

The parameters of the selected materials in the simulation environment are shown in Tables 1 and 2 below. Table 1 shows the geometry of the antenna and Table 2 shows the properties of the blood. In addition, a relative permittivity of 43.03, 2.03 and 2.311 is chosen for the liver, the internal dielectric of the antenna and the Tefzel ETFE (catheter material); with a conductivity of
1.69 S/m also for the liver. The influence of slot size and position on the antenna heat distribution was then digitally examined using a 10 W microwave generator for 15 minutes.

### Table 1. Antenna dimensions

| Property                      | Value (mm) |
|-------------------------------|------------|
| Central conductor diameter    | 0.290      |
| Outer conductor inner diameter| 0.940      |
| Outer conductor outer diameter| 1.190      |
| Catheter diameter             | 1.790      |

### Table 2. Properties of blood

| Parameter                | Value      |
|--------------------------|------------|
| Temperature (°C)         | 37         |
| Density (kg/m³)          | 1045       |
| Perfusion rate (1/s)     | 0.0036     |
| Specific heat (J/kg K)   | 3639       |

3. **Results**

3.1. **The effect of using tapered slot**

The tapered slot resulted in an improvement in tissue strength in all cases with respect to the corresponding non-conical slit, but with a diameter equal to that of the tapered end. The geometry of the inwardly tapered slot, despite the same dimensions as the outwardly tapered slot geometry, allowed better tissue power absorption. The results of the impact of the tapered slot located at a distance of "y" = 4 mm on the total power dissipation density and the thermal properties are shown in figure 2, both inwardly and on the inside, outside to 1.10 mm as base diameter.

![Figure 2. Total power dissipation density dependency on slot geometry](image_url)
3.2. Coaxial antenna slot location effects

It was observed that the total power dissipation density is a function of the position of the slot, i.e. its location from the tip of the antenna. Figure 3 is a graph showing the total power dissipation density versus slot location from the tip of the coaxial antenna for a slot size of 1.10 mm in diameter. The fraction of the power absorbed by the tissue increased as the position of the slot from the tip of the antenna increased. However, at a distance ‘y’ = 6 mm, the power absorbed was at the maximum and the subsequent increase of the distance of the antenna led to a reduction of the absorbed power.

![Figure 3. Effect of slot position on total power dissipation density](image)

The distribution of the temperature in the tissue determines the necrosis of the tissue, depends on the recorded input power and thus on the position of the slit. Figures 4 and 5 show the temperature distribution and the proportion of tissue necrosis reached for the different positions of the coaxial slots. It was observed that the proportion of the necrotic tissue at a 1.5 mm radius position of the coaxial antenna axis, indicating a spherical ablation zone with a diameter of 3 mm, at a position slot ‘y’ = 6 mm according to the position of the slot has the maximum, the maximum is the absorbed power absorbed, as well as the position of the temperature peak distribution values.
Figure 4. Thermal properties of the tissue relationship with slot position

4. Discussion

Using regression analysis, the model can be used to predict the impact of slot position for a slot diameter of 1.1 mm on the total power dissipation density. The model is illustrated in Figure 5.
Figure 5. Model to predict the influence of slot position on total power dissipation density with a 1.1 mm slot diameter.

The effect of the slot position from the coaxial antenna tip on the total power dissipation density is governed by the quadratic equation;

\[
TPDD = 0.1364y^2 + 1.6441y + 4.4834
\]

The "R-squared" value of the model is very close to "1", which suggests that the predictions made with the model will be very close to the real values, making it a reliable predictor.

5. Conclusions

There is a correlation between the total loss power density, the temperature distribution in the tissue, and the proportion of necrotic tissue. The distribution of the temperature of the antenna in the tissue depends on the geometry of the slot. The position of the slot from the tip of the coaxial antenna is a determining factor in the total power dissipation density and temperature distribution, and there is a distance "y" at which the performance of the coaxial antenna is optimized. For this study y = 6 mm.

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