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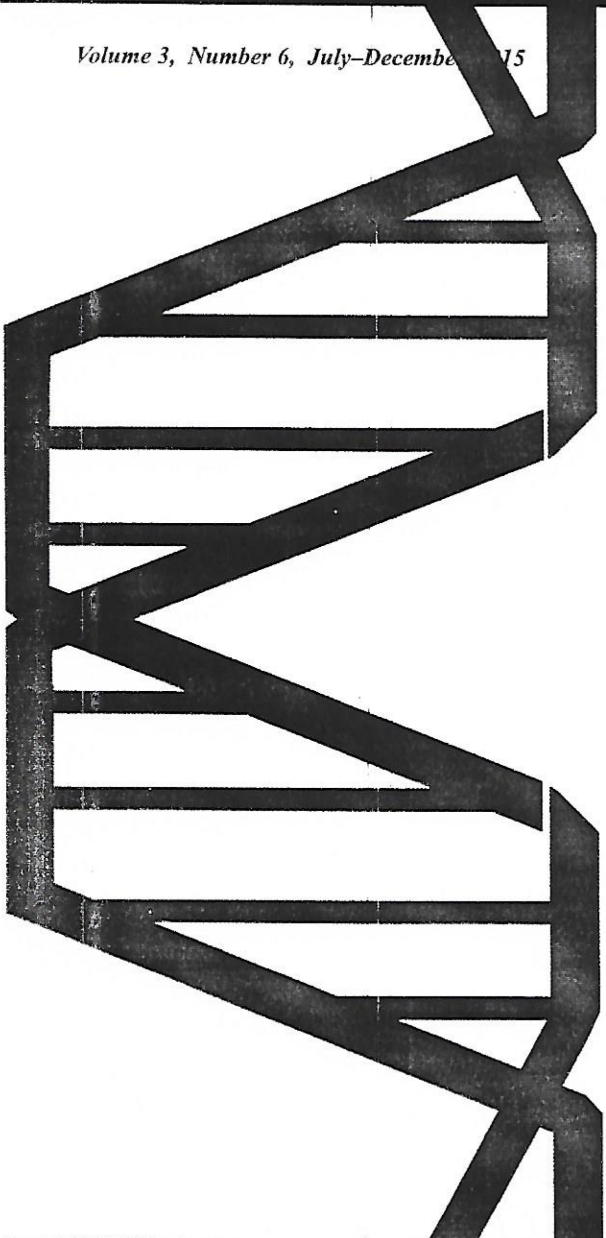



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# A Dual Slot Antenna with a Floating Metallic Sleeve for Microwave Ablation of Liver Tumour

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## ABSTRACT

**Background:** Many antennas had been proposed to deliver localized electromagnetic wave to the tumour. Some of these antennas are not without shortcomings especially high power reflection coefficient, low power dissipation into the tissue, heat elongation on the antenna feedline, and excessive backward heating along the antennas shaft.
**Objective:** To design a new antenna with the intention to create large ablation volume, high aspect ratio and low backward heating for microwave ablation of tissues.
**Materials and Methods:** Finite Element Methods (FEM) in the COMSOL MULTIPHYSICS™ software was used to design and simulate antennas and to study the electromagnetic field and thermal distributions in the liver tissue. Two antennas were fabricated from coaxial cable and connected to solid state microwave generator operating at 2.45 GHz. The powers were set at 30, 40, 80, and 120 W at ablation durations of 120 and 300 s.
**Results:** The best optimized design produced reflection coefficient of –25.3 dB and aspect ratio of 0.81. About 29.5% backward heating reduction along antenna shaft was achieved during the simulation. In most cases there was no statistical difference between simulated and experimented results in aspect ratios, ablation diameters and ablation lengths of the designed antenna.
**Conclusion:** The experimental validation results established that inclusion of a floating metallic sleeve on dual slot antenna for MW ablation increased ablation diameter and aspect ratio as well as decreased backward heating.

**Keywords:** Aspect ratio, dual slot, finite element method, microwave ablation, reflection coefficient.

## INTRODUCTION

Thermal tumour ablation is becoming an alternative in the treatment of many types of cancers such as the lung, liver, bone, kidney and breast (1–4). Many techniques are now in use to deliver heat to tissue, which include microwave, 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! and above in order to destroy cells within a localized region of tumour (3, 5).

Microwave ablation (MWA) is a form of dielectric heating where the dielectric material is the tissue. Dielectric heating occurs when an electromagnetic (EM) field is applied to an imperfect dielectric material. Heating will always occur when 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 (2, 6). The rate of EM energy absorption will be high if the water content of the tissue involved is high. Tissue thermal conductivity (ó) and relative permittivity (år) are other factors that affect the EM absorption efficiency in tissues (3, 7–8).

Several antennas for MWA have been proposed for effective treatment of tumours. These include monopole antenna, dipole antenna, slot antenna, tri-axial antenna, cap-choked antenna and helical antenna (7–11). Many of these antennas are not without drawbacks such as high power reflection coefficient, significant backward heating and high dependence on insertion depth. Antenna 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 (7–8). Dual slot antenna has been reported to produce higher sphericity index than single slot antenna and others. Despite this advantage, specific absorption rate (SAR) tail along the antenna is still conspicuous. The objective of this study is to design a dual slot antenna with a floating metallic sleeve to reduce SAR tail (backward heating) to the barest minimum and also to evaluate the effect of a floating sleeve on the power reflection coefficient, SAR pattern and aspect ratio.

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 (6–7). A 2-D finite element method (FEM) is one of the numerical methods to determine the absorbed power, temperature profile, SAR, and reflection coefficient patterns in tissues. The use of FEM in designing of antenna for MW ablation has been extensively discussed in the literature (12–13). Antenna's specific absorption rate (SAR) pattern and frequency-dependent reflection coefficient in tissue are essential for the optimization of antenna for microwave ablation. 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 is the conversion of MW energy to thermal energy.

### Numerical Modeling

The ultimate goal of computer models for MW tissue ablation is to predict the induced tissue damage. The temperature profile in tissue during ablation procedure depends on the interaction of microwaves with tissue and heat transfer in tissue.

### Interaction of Microwave with Tissue

The propagation and absorption of microwaves in tissue is governed by Maxwell's equations stated as (13):

$$\nabla . D = \rho_{free} \quad (1)$$

$$\nabla . B = 0 \quad (2)$$

$$\nabla . E = \frac{\partial B}{\partial t} \quad (3)$$

$$\nabla . H = J + \frac{\partial D}{\partial t} \quad (4)$$

Where **D** [C/m$^2$] is electric flux density, **B** [T] is magnetic field, **E** [V/m] is electric field strength, **H** [A/m] is magnetic field intensity, $\rho_{free}$[C/m$^2$] is free charge density, and **J** [A/m$^2$] is current density. The electromagnetic fields radiated in tissue by a given antenna can be determined by solving Maxwell's equations, given knowledge of tissue electromagnetic properties (permittivity and conductivity) and appropriate initial and boundary conditions.

### Heat Transfer in Tissue

The most widely used equation for modeling thermal therapy procedures is the Pennes' bioheat equation (11):

$$\rho C \frac{dT}{dt} = \nabla . k\nabla T + Q - Q_p + Q_m \quad (5)$$

Where ñ is the tissue density [kg/m$^3$], C is the specific heat capacity at constant pressure [J/kg·K], 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.

### Thermal Tissue Damage

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

$$\Omega(t) = \ln\left[\frac{C(0)}{C(t)}\right] = \int_0^t \exp\left(-\frac{Ea}{RT(T)}\right)dt \quad (6)$$

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, Ea (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 T (K) is the absolute temperature of tissue. Percentage of dead tissue, P, can be determined by using (7)

$$P = 1 - e^{-\Omega} \quad (7)$$

From the above equation when Ω = 1, there is 63% percent probability of cell death and it corresponds to when tissue coagulation first occurs and tissue perfusion ceases.

## MATERIALS AND METHODS

### Computer Simulation

The modeling of the antennas was based on the use of a 50 Ω UT-0.0852 semi-rigid coaxial cable. Two slots (S1 and S2), each of width 2 mm, were cut on the outer conductor to allow EM wave propagation into the tissue. The separation length between the two slots was 8 mm. Finite element (FE) package (COMSOL Multiphysics™) – heat and electromagnetic modules – was used to determine antenna efficiency and performance. In addition, this software package allows us to specify the geometry of antenna, solves the Maxwell's equations and the heat equations in the surrounding tissues (14). The model involves the antenna inserted into large piece of liver. Two antennas were modeled: one without metallic sleeve and the second with metallic sleeve both of the same radii. In this study, average value of relative permittivity (43.03) and effective conductivity (1.69 S/m) were taken from Yang *et al.* and some other literature (17–19).

The asymmetric FE model was discretized using adaptive triangular element with a maximum element size of 3 mm and Lagrange quadratic was used to approximate MW power absorbed. The external surface of the liver acted as boundary for the computational domain. A low reflecting boundary was thermally isolated. Metallic components were assumed to be perfect electric conductors (PECs) and the coaxial dielectric was assumed to be lossless PTFE. Perfectly matched layers were assumed for all exterior boundaries. Input power was set to 120 W at 2.45 GHz in all simulations. The aspect ratio, ablation diameter and ablation length were determined using ImageJ v 1.47 (National Institute of Health, NIH).

### Experimental Validation

Antennas with sleeve and without sleeve were fabricated from 0.0852 semi rigid coaxial cable (RG405 Coax, Pasternack Enterprises Inc, Los Angeles, CA) to match the simulated antennas geometries. The microwave source was connected to a 2.45 GHz solid-state MW generator (SAIREM SAS 200 W, Neyron-Cedex, France). Generator output power was employed to offset cable losses and ensure appropriate power delivery to the antenna. Experimental ablations were created in blocks of normal *ex-vivo* bovine liver obtained from animal slaughter house initially at temperature between 27 and 30°C. Heating was performed with input powers of 20, 30, 40 and 50 W for 3, 5 and 10 min. Real time temperature measurements at points approximately 10 and 20 mm from the probe surface were recorded using 4-Channel Datalogging Thermometer (SPER Scientific Ltd.).

## Statistical Analysis

Ablation lengths, ablation diameters and aspect ratios were measured and recorded as mean ± standard deviation (SD) for both simulation and experimentation results. Statistical analyses for all the data were performed using Statistical Package for Social Sciences (SPSS) version 20. Student2 s t-test was used to compare the results of the two antennas (antenna with and antenna without sleeve). A value of $p<0.05$ was considered statistically significant.

## RESULTS

### Simulation Results

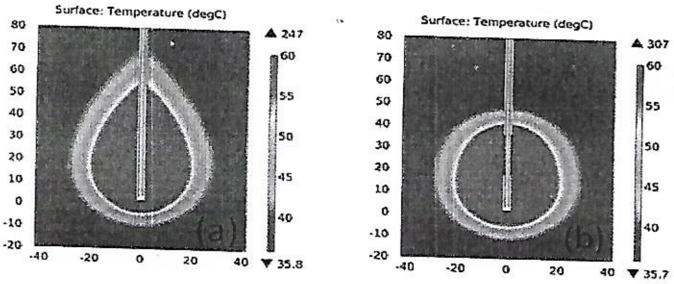


**Fig. 1: Temperature distribution. With 60°C isocontour, ablation length reduced longitudinally along the antenna shaft from 59.3 mm to 43.6 mm when sleeve was inserted while there is slight increase in ablation diameter from 37.9 mm to 38.8 mm.**

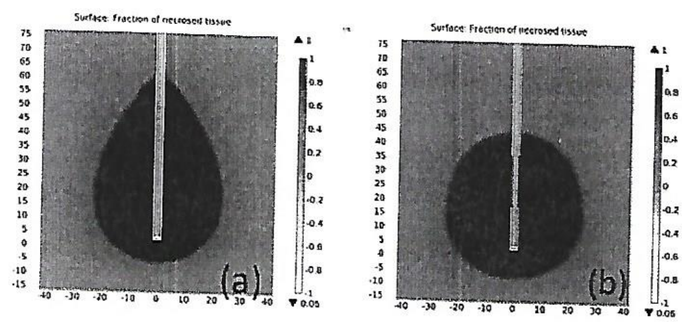


**Fig. 2: Plots of fraction of necrosed tissue with an input power of 50 W at 600 s for antenna (a) without sleeve and (b) with metallic sleeve. The longitudinal length decreased from 60.6 mm to 43.6 mm and ablation diameter increased from 33.8 mm to 37.9 mm.**

### Experimental Validation Results

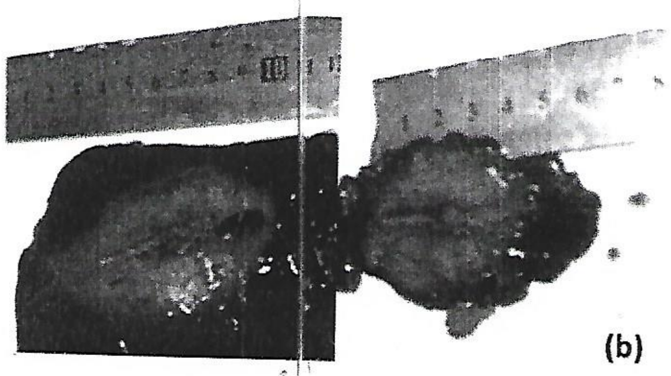


**Fig. 3: Ablation lesions produced by antenna with sleeve (a) and antenna without sleeve (b) in ex-vivo bovine liver. Input power was 40 W at 10 min. ablation durations. Lesion on the left was about 57.5 by 41.6 mm while lesion on the right was about 66.8 by 38.7 mm of aspect ratio 0.71 and 0.53 respectively.**

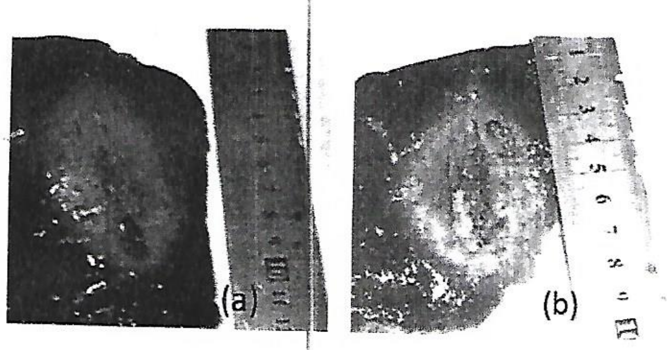


**Fig. 4: Ablation lesions created by antenna with sleeve (a) and antenna without sleeve (b) in *ex-vivo* bovine liver. Input power was 50 W at 10 min. ablation durations. Lesion (a) was about 57.6 by 45.6 mm while lesion (b) was about 64.8 by 35.5 mm of aspect ratio 0.79 and 0.55 respectively.**

## DISCUSSION

Most of the designed and simulated designs with a floating metallic sleeve (106 out of 121) were characterized by either high reflection coefficient or low aspect ratio or both. The results indicate that temperature, power dissipation density and specific absorption ratio (SAR) and necrotic distributions pattern are grossly affected by placement position and length of the sleeve as shown in Figures 1 and 2. Generally, it was observed that when sleeve length is less than 14 mm and greater than 22 mm the SAR tails are significant. Increases in aspect ratio and decreased in ablation length are attributed to the presence of a floating sleeve on the antenna. It was also observed that, inclusion of a floating metallic sleeve on the designed dual slot antenna provides much localized power deposition in hepatic tissue with minimal backward heating, and low power reflection.

Many researchers have reported various method of optimizing double slot antennas; despite low power reflection coefficients reported, backward heating is one of their

**Table 1: Summary of Difference between Simulation and Experimental Results**

| Parameter | Power (W) | Result | Ablation Duration (min) 3 | 5 | p value |
|---|---|---|---|---|---|
| Aspect Ratio | 30 | 1 | 0.74±0.61 | 0.86±0.92 | p=0.50 |
| | | 2 | 0.87±0.02 | 0.86±0.01 | |
| | 40 | 1 | 0.77±0.52 | 0.83±0.77 | p=0.87 |
| | | 2 | 0.79±0.04 | 0.80±0.06 | |
| | 80 | 1 | 0.85±0.37 | 0.91±0.26 | p=0.09 |
| | | 2 | 0.69±0.01 | 0.70±0.01 | |
| | 120 | 1 | 0.86±0.12 | 0.93±0.35 | p=0.16 |
| | | 2 | 0.68±0.03 | 0.63±0.01 | |
| Ablation Diameter | 30 | 1 | 28.08±0.8 | 34.7±0.6 | p=0.06 |
| | | 2 | 25.4±1.1 | 31.5±1.7 | |
| | 40 | 1 | 30.1±0.4 | 36.2±0.9 | p=0.03 |
| | | 2 | 32.1±0.5 | 38.0±1.0 | |
| | 80 | 1 | 37.1±0.3 | 44.7±0.6 | p=0.33 |
| | | 2 | 34.0±0.5 | 33.7±0.3 | |
| | 120 | 1 | 40.2±1.3 | 47.5±1.4 | p=0.95 |
| | | 2 | 43.6±1.4 | 44.6±0.7 | |
| Ablation Length | 30 | 1 | 36.6±0.6 | 39.9±0.9 | p=0.42 |
| | | 2 | 32.1±1.4 | 39.3±0.8 | |
| | 40 | 1 | 39.0±0.4 | 43.3±0.3 | p=0.82 |
| | | 2 | 38.5±1.0 | 44.2±1.1 | |
| | 80 | 1 | 37.1±1.2 | 44.7±0.6 | p=0.06 |
| | | 2 | 48.9±0.4 | 54.5±0.3 | |
| | 120 | 1 | 44.2±0.5 | 47.5±0.6 | p=0.04 |
| | | 2 | 64.7±1.5 | 70.4±1.0 | |

*1 = Simulation; 2 = Experimentation.*

drawbacks (6-8). Also, it has been reported previously that aspect ratio, ablation length and ablation diameter are input power and ablation duration dependent.

Robust applicators (antennas) for hepatic MW ablation have been suggested by many authors for ablation of liver tissues (6-7, 9-10, 19). More studies are still ongoing to extend MW ablation to the treatment option for tumours of kidney, lung and bone which exhibit a relatively spherical morphology. Devices capable of creating larger ablation are desirable to treat tumours above 3 cm without resulting to the use of multiple antennas as in radiofrequency ablation (RFA) procedures.

In comparison with antenna without a sleeve as in Figures 1–4, this new designed antenna demonstrates that floating sleeve insertion on dual slot antenna for MW ablation increased aspect ratio by 41.4 % and decreased ablation longitudinal length along the antenna shaft by 13.9 % whereas ablation diameter increased slightly by 5.8 %.

Similarly, differences between the experimental and simulated results are small for ablation length (3.9%), ablation diameter (5.4%) and aspect ratio (7.5%). Temperature differences in the range of 25 to 30% were also recorded between simulation and experimental values measured at 10 mm and 20 mm from the surface of the antenna. However, the differences in the results of necrotic patterns might be due to inhomogeneity of tissue cellular structure, variation in tissue properties, tissue water evaporation, water condensation and water movement during ablation (3, 19).

This present design was constrained by slight increase in diameter of the antenna, which might limit its percutaneous applications. Research is on going to design smaller antenna intended for percutaneous applications to avoid risk of complications such as bleeding and pneumothorax.

## CONCLUSION

A new antenna with good performance had been designed and simulated for microwave ablation of liver tissue using COMSOL MULTIPHYSICS™ software. The experimental validation results established that inclusion of a floating metallic sleeve on dual slot antenna for MW ablation increased ablation diameter and aspect ratio as well as decreased backward heating.

## ACKNOWLEDGMENTS

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## CONFLICT OF INTEREST

No conflict of interest in respect of this study.

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