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DESIGN AND OPTIMIZATION OF A WATER COOLED ANTENNA FOR MICROWAVE ABLATION USING FINITE ELEMENT METHOD

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ABSTRACT

Microwave ablation is a technique for treating cancerous tissues with the application of heat. Some tumors are located such that they cannot be successfully treated with conventional external radiation beam techniques. Microwave ablation is currently an alternative option being considered for the treatment of unresectable tumors. In this study, we designed a water cooled microwave antenna for tumor ablation. The water cooled antenna for hepatic microwave ablation was designed using Finite Element Methods (FEMs) (COMSOL MULTIPHYSICS^{TM} version 4.4). Finite element methods were used to study the electromagnetic (EM) field and thermal distributions in liver. The water slot position, water slot length and the antenna slot length, from the tip of the antenna ($z = 0$ mm) were varied within the ranges ($43 \leq z \leq 60$ mm), ($1 \leq z \leq 10.5$ mm) and ($1 \leq z \leq 20$ mm) at 1 mm, 0.5 mm and 0.5 mm interval respectively, at a frequency of 2.45 GHz. The design has reflection coefficient of -25.5dB, with 94.0% power dissipation into the tissue. Experimental validation shows that the inclusion of a cooling unit reduces the backward heating and increases the power deposition into liver tissue.

Keywords: Microwave, Tumor ablation, Cancer, Reflection coefficient, Water cooled antenna.

INTRODUCTION

Hepatocellular carcinoma (HCC) is one of the most common malignant tumors with an estimated 1,000,000 worldwide death per year (Andriulli et al, 2004). Primary and secondary malignant hepatic tumors are among the most common tumors worldwide (Nwoye et al, 2014, Erce et al 2003, Swift et al, 2003). Microwave Ablation (MWA) is a promising technology for the treatment of hepatic tumors. The goal of MWA is to destroy the tumor along with a 1 cm margin of normal hepatic tissue (Nwoye et al, 2014a). This technology has been used in both intraoperative and percutaneous approaches for primary hepatocellular carcinoma and hepatic metastasis of colorectal carcinoma (Dodd et al, 2000, Yanget al, 2003, Gaiani et al, 2006). Thermal tumor ablation is becoming an alternative in the treatment of many types of cancers such as lung, liver, bone, kidney and breast (Brace et al, 2009). The goal of thermal ablation energy source is to elevate tissue temperatures enough to create zones of irreversible cellular damage. For some patients, removal of tumors with open surgery is not possible or involves high risk due to the poor condition of the patient. The use of minimally invasive surgery or percutaneous intervention may in this case be adequate and offers advantages such as safety, reduced trauma (Diederich et al, 2005) and reduced operative time (Boni et al, 2006). The principle of the microwave ablation technique depends on heating the tissue in order to kill cancerous cells. During MWA, intense heat in the targeted tissue close to the applicator tip is generated and the heat is conducted along the shaft of the device. Futhermore, heat is generated inside the coaxial line of the applicator due to electric losses in the cable. To avoid burns to normal tissue in contact with the shaft when using a percutaneous procedure, a cooling unit needs to be incorporated into the applicator to maintain the temperature of the shaft below a regulatory imposed safety limit of 41 ^{0}C (Underwriters Laboratories, 2003). Antennas with water cooling were already developed by (Liu Y et al, 2007), and (Qun Nan et al, 2007). Several other interstitial antennas for MWA have also been reported in the literatures and the related field for interstitial microwave ablation. These include coaxial monopoles, dipoles, annular slots, and triaxial and looped designs. However many of the designs are characterized by elongated heating patterns (Labonte et al, 1996, Bertram et al, 2006). The objective of this study is to design a water cooled antenna to reduce SAR tail (backward heating) to the barest minimum, and to determine the most optimal geometry to produce low reflected power and high power dissipation. To assist in antenna design for MWA, many researchers have employed Mathematical models in computational electromagnetics (CEM). The widely used equation for modeling thermal therapy procedures is the pennes' bioheat equation (Penes et al, 1948).

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

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].$\mathrm{Q_p}$is the heat loss due to blood perfusion (W/m^3) and $\mathrm{Q_m}$ 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 tissue exposed to elevated temperature is given by (Prakash et al 2010):

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

where C(0) is the original concentration of undamaged cells prior to heating, C(t) is the concentration of undamaged cells after heating. Ωis a dimensionless damage parameter. A (1/s) is frequency factor, $\mathrm{E_a}$ (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 T (K) is the absolute temperature of tissue.

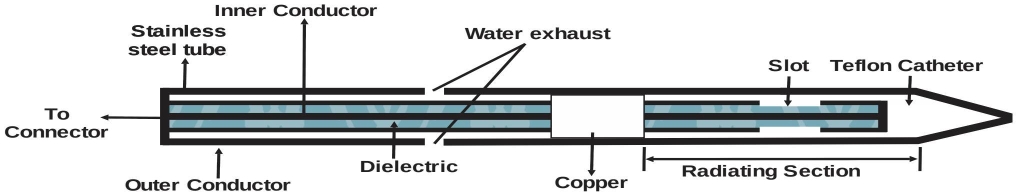


Figure 1: Sketch of the radiating portion of the antenna with cooling unit

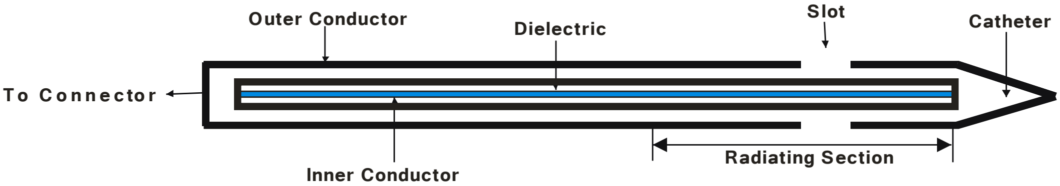


Figure 1: Sketch of the radiating portion of the antenna without cooling unit

MATERIAL AND METHODS

Antenna Simulation

Two antennas were developed; one with cooling unit and the other without cooling unit (Figure 1 and Figure 2). Finite element (FE) package (COMSOL MULTIPHYSICS^{TM}, was used to determine their performance. This software allows us to specify the geometry of antenna, solves the Maxwell's equations, the heat equations and the heat transfer in fluid in the surrounding tissue. Three important parameters were varied; they are the antenna slot length where the MW energy passes into the tissue, water slot length where the water passes from the cooling unit into the antenna shaft, thereby cooling the shaft of the antenna to protect some neighboring organ at risk of high powers. The water slot position, water slot length and the antenna slot length, from the tip of the probe ($z = 0$ mm) were varied within the range ($43 \leq z \leq 60$ mm), ($1 \leq z \leq 10.5$ mm) and ($1 \leq z \leq 20$ mm) at 1 mm , 0.5 mm and 0.5 mm interval respectively, using operating frequency of 2.45 GHz. 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. The computer simulations for each antenna were in two fold. The first group was simulated with an input powers of 20, 30, 40 and 50 W for 3, 5 and 10 mins. While the second group with input powers of 60, 80, 100, 120 W for 2, 4 and 7 mins. The lesion size and shape were calculated using the 60 ^{0}C isocontour for 180 s.

Experimental validation

Ex-vivo experiments were performed to validate simulated antenna results. The two antennas were fabricated from 0.085′ semi rigid coaxial cable (RG4405 Coax, Pasternack Enterprises Inc, Los Angeles, CA). We ensured that simulated and fabricated antennas match geometrically. The antenna was connected to a 2.45 GHz solid-state MW generator (SAIREMSAS 200W, Neyron-Cedex France), with a variable power from 0 to 200 W in step of 1 W for different time durations. Liver obtained from animal slaughter house was divided to two groups. The first group was heated using input powers of 20, 30, 40 and 50

W for 3, 5 and 10 min. The second group was heated using power inputs of 60, 80, 100 and 120 W for 2, 3 and 5 min. Real time temperature measurements at points approximately 5 and 10 min from the probe surface were recorded using 4-channel Datalogging Thermometer (SPER Scientific Ltd). Each ablated tissues was sliced along the axis of the antenna to evaluate its maximum dimensions (diameter and length).

Statistical Analysis

Statistical analysis were done using SPSS (version 16) package. Results are presented as mean ± S.E.M. Differences between means were determined by Student's t-test and $P<$ 0.05 was considered significant.

RESULTS

Table 1: Dimensions of the antenna

Parameters	Value
Outer conductor diameter	0.51 mm
Dielectric diameter	1.16 mm
Inner conductor diameter	0.52 mm
Stainless steel	0.60 mm
Diameter of Teflon	1.75 mm
Slot size S16.50 mm	
Water Slot size S2	2.00 mm

Table 2: Best simulated designed antenna with cooling unit at 50 W

Serial Number	Water Slot Position (mm)	Reflection Coefficient (dB)	Power Dissipation (W)
1	40	-15.61	45.91 (91.82%)
2	41	-14.88	45.67 (91.34%)
3	42	-14.55	45.62 (91.24%)
4	43	-18.70	46.59 (93.18%)
5	44	-21.47	46.85 (93.69%)
6	45	-23.81	46.96 (93.92%)
7	46	-25.34	47.00 (94.01%)
8	47	-25.21	46.99 (94.00%)
9	48	-23.80	46.96 (93.92%)
10	49	-22.36	46.92 (93.83%)
11	50	-21.56	46.89 (93.78%)
12	51	-21.48	46.91 (93.81%)
13	52	-21.91	46.94 (93.89%)
14	53	-22.60	46.98 (93.97%)
15	54	-23.23	47.01 (94.02%)
16	55	-23.56	47.02 (94.05%)
17	56	-23.48	47.02 (94.04%)
18	57	-23.11	47.00 (94.01%)
19	58	-22.70	46.99 (93.98%)
20	59	-22.41	46.98 (93.96%)
21	60	-22.35	46.98 (93.96%)

Table 3: Mesh statistics of the antennas with cooling unit (WCU) and without cooling unit (WOCU)

Mesh parameter	Without Cooling unit	With Cooling unit
Triangular element	12884	13993
Edge elements	1830	2088
Vertex element	24	38
Number of elements	12884	13993
Minimum element quality	0.3629	0.05578
Average element quality	0.9515	0.9430
Element area ratio	$7.635\text{x}10^{-4}$	$7.635\text{x}10^{-4}$
Mesh area (mm^2)	2772	2772
Maximum growth rate	3.615	3.851
Average growth rate	1.271	1.263
Degree of freedom	91022	98787
Degree of tissue injury	2957	3299
Solution time (s)	210	237

Table 4: Mean ablation lengths, ablation diameters and axial ratios of antenna with and without cooling unit. (Results presented in mean ± standard deviation)

ANTENNA WITH COOLING UNIT						ANTENNA WITHOUT COOLING UNIT		
Input Power (W)	Ablation Duration (min)	Ablation Length (mm)	Ablation Diameter (mm)	Axial Ratio		Ablation Length (mm)	Ablation Diameter (mm)	Axial ratio
20	3	46.0±1.4	14.8±2.0	0.16		48.0±2.1	14.2±5.9	0.30
	5	47.5±0.4	20.0±1.7	0.21		50.9±1.4	18.8±6.5	0.37
	10	47.9±0.1	26.0±1.4	0.27		54.5±0.1	23.4±7.6	0.43
30	3	47.9±0.1	19.5±1.8	0.21		52.1±0.1	18.5±6.4	0.36
	5	48.3±0.4	15.1±5.6	0.25		54.5±0.7	24.0±5.7	0.44
	10	49.1±1.3	22.1±5.7	0.31		57.4±0.6	30.5±6.4	0.53
40	3	48.2±0.4	22.5±1.5	0.22		54.3±0.4	21.8±5.9	0.40
	5	52.8±1.1	29.6±1.4	0.28		56.6±0.8	27.8±5.4	0.49
	10	54.2±0.1	36.8±0.8	0.33		58.0±2.8	34.1±5.8	0.59
50	3	56.9±0.1	26.4±1.0	0.25		56.2±0.2	24.4±6.2	0.43
	5	58.0±0.1	29.0±0.7	0.29		58.7±0.2	30.7±5.2	0.52
	10	63.3±0.1	33.0±0.7	0.34		64.6±3.7	37.3±6.6	0.58
60	2	49.8±0.4	28.0±1.4	0.22		51.1±1.6	18.5±6.4	0.36
	4	52.8±1.8	34.0±1.1	0.30		53.1±0.8	21.6±6.2	0.41
	7	56.1±0.1	38.2±1.3	0.33		55.6±0.6	27.9±5.5	0.50
70	2	48.6±0.6	25.0±1.4	0.23		56.5±0.6	24.0±5.7	0.43
	4	52.8±0.3	33.1±1.1	0.30		59.4±0.8	32.0±5.7	0.54
	7	57.9±0.2	42.0±1.4	0.34		67.5±0.8	39.0±4.2	0.58
80	2	54.2±7.1	26.0±1.4	0.24		57.9±0.1	24.5±6.4	0.42
	4	53.7±0.3	34.9±0.8	0.31		63.5±0.7	33.2±4.5	0.52
	7	57.5±3.6	43.0±0.7	0.35		69.8±0.4	42.0±2.8	0.60
90	2	58.0±8.4	32.0±1.4	0.26		58.4±0.6	26.2±5.4	0.45
	4	55.0±0.1	36.5±0.9	0.32		64.9±1.3	35.2±4.5	0.54
	7	64.0±0.1	44.4±0.6	0.35		72.2±1.5	43.5±3.5	0.60
100	2	51.6±0.8	28.0±0.9	0.26		65.2±0.7	33.0±4.2	0.51

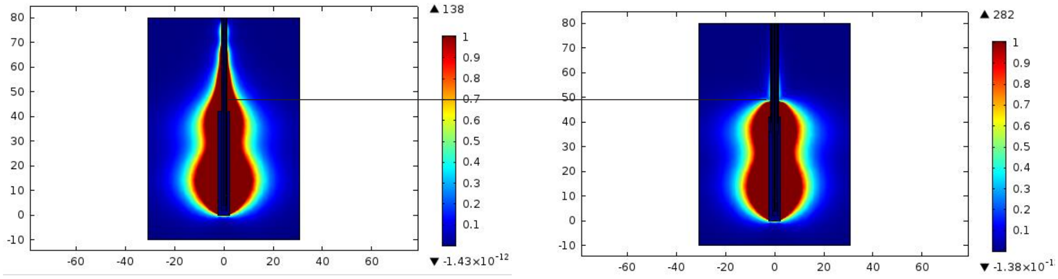
	4	55.8±0.4	37.5±1.1	0.32		67.3±0.4	37.0±4.2	0.55
	7	64.6±0.8	45.1±0.8	0.37		73.5±0.7	44.1±4.9	0.60
110	2	50.0±0.1	33.0±0.7	0.28		60.9±0.5	28.5±4.9	0.47
	4	55.9±0.2	38.0±1.4	0.33		68.1±0.1	37.2±4.5	0.55
	7	67.9±0.2	45.2±0.6	0.36		74.5±0.6	45.9±5.5	0.62
120	2	50.7±0.3	31.0±0.7	0.29		74.2±0.1	44.0±5.7	0.59
	4	58.2±0.1	39.4±0.7	0.34		73.5±0.7	43.8±5.4	0.60
	7	68.1±12.7	48.5±0.4	0.37		73.7±0.8	44.6±3.7	0.61

DISCUSSION

Variation in the antenna slot size, water slot size and water slot position affect the Specific absorption rate (SAR) distribution pattern, longitudinal ablation length, reflection coefficient and ablation radius. The optimal design has a reflection coefficient of -25.34 dB at operating frequency of 2.45 GHz when antenna slot size is 6.5 mm, water slot length 2 mm and water slot position of 46 mm. From Table 3, it was observed that the element area ratio and the mesh area were the same for both antennas. The result from the simulation also shows that the antenna with cooling unit has larger number of degree of tissue injury, degree of freedom, triangular element with minimum element quality, vertex element and edge element. This shows that the antenna with cooling unit has better geometry and higher efficiency than the antenna without cooling unit. Moreso, in Table 4, there is significant difference between the mean of ablation lengths ($p < 0.05$) and there is no significant difference in the mean of ablation diameter ($p > 0.05$).

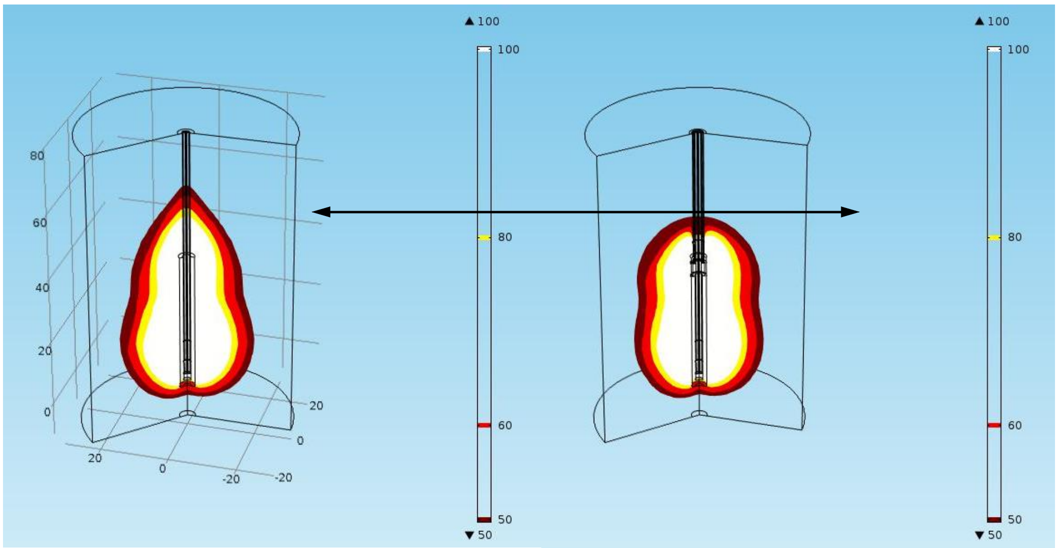
The top 21 best simulated antennas with cooling unit are presented in Table 2. The pattern of total power dissipation density, and SAR are significantly affected by water slot position and length as shown in Figures 3,4and 5. Generally, it was observed that variation of the water slot position greatly affects the reflection coefficient and the total power deposition as shown in Table 2.(Yang et al, 2006, Bertram et al, 2006a). Studies show that the size of the tumor is an important factor determining the local recurrence rate (Mulier et al, 2005). When more than one treatment is needed to ablate a tumor, higher risk of local recurrence has been described (Adam et al, 2002). This study presents a microwave antenna which use high power with the inclusion of a cooling unit to ablate large tumors up to 68.1 mm in one session as shown in table 4. This is definitely an advantage and minimizes the risk of local recurrence. The water cooled antenna is also capable of delivering power of 100 to 200 watts at 2.45 GHz to treat lesions up to 5 cm which is similar to the work done by Swift et al, (2003).

Morphologically, the cancerous cell is characterized by a large nucleus, having an irregular size and shape (Baba et al, 2007) As shown in Figures 4a, 5a and 6b, the ablation area for the antenna without sleeve was pear-like while in Figure 4b, 5b and 6a, the antenna with cooling unit has a dumbbell shape. This is similar to the work presented by Qun Nan et al. As seen from the results of this study, we have been able to design an antenna with low reflection coefficient of -25 dB compared with -19.78 by Yang et al., -22.40 by Bertram et al. , and -20.87 by Ibitoye et al. designs.



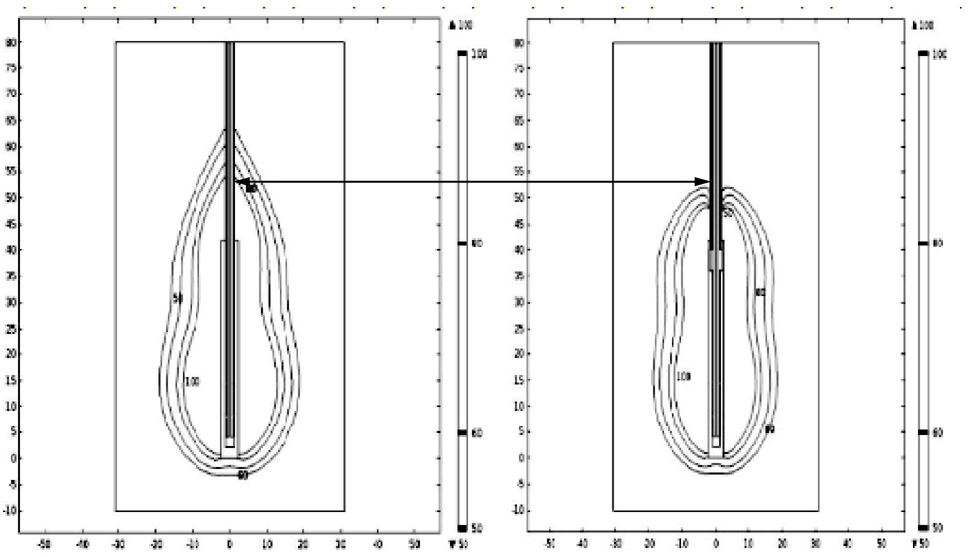
3a 3b

Figure 2: Total power dissipation density distribution in tissue for antenna (a) without (b) with cooling unit



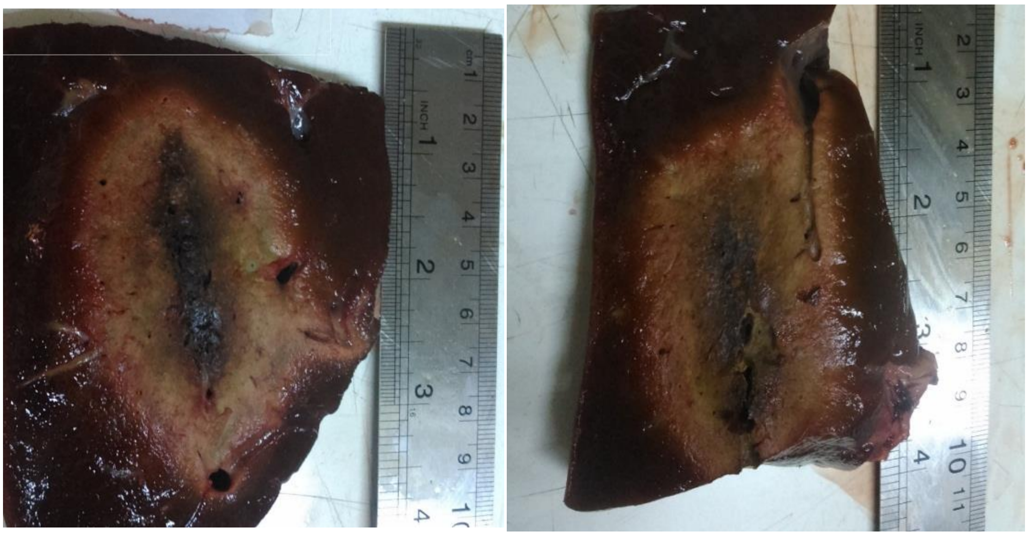
4a 4b

Figure 3: 3-D isosurface for antenna (a) without (b) with cooling unit for 180s



5a 5b

Figure 4: Isothermal contours for 50, 60, 80 and 100 ^{o}C for antenna (a) without and (b) with cooling unit for 180s



6(a) 6(b)

Figure 5: Ablation lesions produced by (a) Antenna with cooling unit (b) Antenna without cooling unit

In Figure 3, the figure shows maximum power density dissipation for antenna without cooling unit off 138 MW/m^3 while the inclusion of the cooling unit increased the power dissipation into the tissue to a maximum of 282 mw/m^{3}also the power dissipation length along the antenna shaft was reduced from 76 mm to 49 mm. In Figure 4 backward heating along antenna shaft was reduced by the cooling unit as shown in Figure 4(b), temperature distribution in 3-D at 50, 60, 80 and 100 ^{o}Cisosurface decrease from 70 mm to 59 mm. In Figure (5) with 50 ^{o}Cisocontour, ablation length reduced longitudinally along the antenna shaft from 65 mm to 52 mm when cooling unit was used. Overall, the results of the simulated antennas Figure (3) to Figure (5) are similar to the work reported by (QunNan et al, 2007, Ibitoye et al, 2015) and shows that the problem of backward heating along the antenna shaft and the inability to deliver sufficient power to the tumor (Bertram et al, 2006, Brace et al, 2010) can be addressed using water cooled antenna. Differences between the experimental and the simulated result are not marginal for ablation length and ablation diameter. The lesion in figure 6a was about 76 mm by 41 mm while the lesion in figure 6b was about 61 mm by 38 mm.

CONCLUSION

We have demonstrated that inclusion of cooling unit on the antenna reduces backward heating along the antenna shaft and it is able to deliver higher power to ablate large tumors up to 5 cm in one session.

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Conflict of Interest: None

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