MICROWAVE ANTENNAS FOR MINIMALLY INVASIVE THERMAL THERAPY

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Abstract: This paper presents an overview on the procedures for analyzing and design of microwave antennas for cardiac ablation and thermal therapy of cancerous tumors. The numerical technique based on the Finite-Difference Time-Domain (FDTD) method is used to calculate the Specific Absorption Rate (SAR) deposited into the tissue by the microwave antenna. The SAR values are then used to calculate the thermal distribution within the tissue by using the bioheat transfer equation (BHTE). The results indicate the effectiveness of proposed microwave thermal therapeutic techniques.

Key words: Microwave antennas, cardiac ablation, thermal therapy, cancer, FDTD.

1. Introduction

Over the past decade there has been an increased interest in the application of microwave energy for medical diagnostics and thermal therapy for the cure of cardiovascular diseases and cancer treatment [1]. Microwave energy application for the ablation of abnormal cardiac tissues for the treatment of heart rhythm disorders is becoming popular [1-3]. Also microwaves are being applied for the treatment of Benign Prostatic Hypertrophy (BPH) which represents enlargement of the prostate gland and for the cure hepatic malignancies and liver metastases. Also microwave thermal therapy is finding applications in Balloon Angioplasty and Microwave assisted Lipoplasty [1]. In all these applications, antennas incorporated inside catheters are used for minimally invasive, laparoscopic and laparatomy procedures. The microwave therapy works on the basis of absorption of electromagnetic radiation by biological tissues which is quantified by the Specific Absorption Rate (SAR).

While the health effects due to long term exposure to electromagnetic energy are still under investigation [6], short term controlled exposure to electromagnetic energy can be clinically used for the above mentioned therapeutic applications [3]. During the clinical applications, using either a percutaneous, laparoscopic or laparatomic routes microwave antennas are advanced to the target tissue using a catheter. Once the antennas are in position, a higher level of microwave energy is applied to a focused area for shorter time duration to cause localized tissue heating. The purpose of producing the localized heating is to raise the local tissue temperature to a point where tissue necrosis occurs thereby destroying the tissue properties [5].

In thermal therapy applications, the applicator plays a fundamental role since the efficiency of heating depends on the characteristics of the applicator. Usually in microwave applications, the applicators are miniaturized antennas that are small in size, light weight and can to a great extent conform to the shape of the targeted tissue [1].

The key factor in the success of the above mentioned treatment modalities is the design of optimum antenna configuration which is capable of delivering high level of microwave energy into the target tissue. With this view in mind, this paper is organized as follows. Section 2 describes the miniaturized antennas and their design and optimization strategies for cardiac ablation and cancer therapy. Section 3 shows in-vitro lesions created using the proposed antennas. Finally conclusions on the investigations reported in this paper are summarized in section 4.

2. Design of Miniaturized Antenna Applicators

The FDTD technique is used in predicting the amount of electromagnetic energy absorbed by biological bodies due to microwave radiation [3, 6]. The amount of energy absorbed by the tissue is quantified by the SAR. In therapeutic applications of microwave energy, it is extremely important to be able to predict the electromagnetic interactions between antennas and the tissues such as cancerous tumors or the myocardial tissue so that the energy deposition in terms of thermal profile is available to estimate the efficacy of the treatment modality.

A general procedure for determining the SAR and subsequently the heat generated within the tissue is depicted in the flowchart as shown in Figure 1.

From the figure it can be seen that within the computational domain, the FDTD technique is used to calculate the amount of electric (***E***) field deposited into the tissue by the antenna. The SAR values are then obtained using equation (1).

$$SAR = \frac{\sigma}{\rho}\left|E_{Total}\right|^2 \qquad (1)$$

where σ and ρ is the conductivity and the density of the tissue surrounding the antenna respectively. Once the SAR values are obtained, the bioheat transfer equation (BHTE) [4] is used to predict the local temperature rise due to the applied microwave energy.

Figure 2 shows the representation of a microwave antenna being placed next to the myocardium. In this case, the computation domain can be constructed with the antenna being surrounded by blood and the myocardium. Within the FDTD computation domain, the blood and the myocardium are differentiated by their respective dielectric constants. The measured dielectric constants of blood and myocardium are also shown in figure 2. Since the antenna is surrounded by inhomogeneous medium, full 3D-FDTD simulation is used to obtain the characteristics of the antenna.

Figure 3 shows rotationally symmetric representation of a microwave antenna inside the hepatic tumor. This rotationally symmetric (RS) representation though is approximate, it can provide a very fast means of calculating the energy deposition and help in the optimization of the antenna characteristics when coupled with FDTD. . For rotationally symmetric geometries, the RS-FDTD as described in [3] can be used in order to reduce the computation time.

We have proposed a novel miniaturized antenna known as the ETW antenna for microwave thermal therapy and ablation [3]. The RS-FDTD is used to design and optimize an expanded-tip wire (ETW) antenna. Figure 4 shows the comparison of measured and simulated reflection coefficients of the ETW antenna within the liquid phantom.

Figure 5 shows the normalized ***E***-field of ETW antenna. Figure 5a shows the normalized ***E***-field of ETW antenna across the cable surface as well as the antenna. Figure 5b shows the spatial distribution of the ***E***-field. From figure 5, it can be seen that after optimizing all the parameters of the ETW antenna, the ***E***-fields are made to confine to the antenna section (between 0mm to 30mm). Also, from figure 5a, it can be seen that the transition of the ***E***-field curve is very smooth. It is important to have a smooth ***E***-field transition to avoid localized hot-spots. Equation (1) is used here to calculate the SAR of the tissues surrounding the ETW antenna. Figure 5c shows the normalized SAR values of tissues surrounding the ETW antenna. From here, it can be seen that due to well distributed ***E***-field, as shown in figures 5a and 5b, the SAR values across the ETW antenna is also very smooth. Since there are no localized peaks of SAR values across the ETW antenna, localized hot-spots can be avoided.

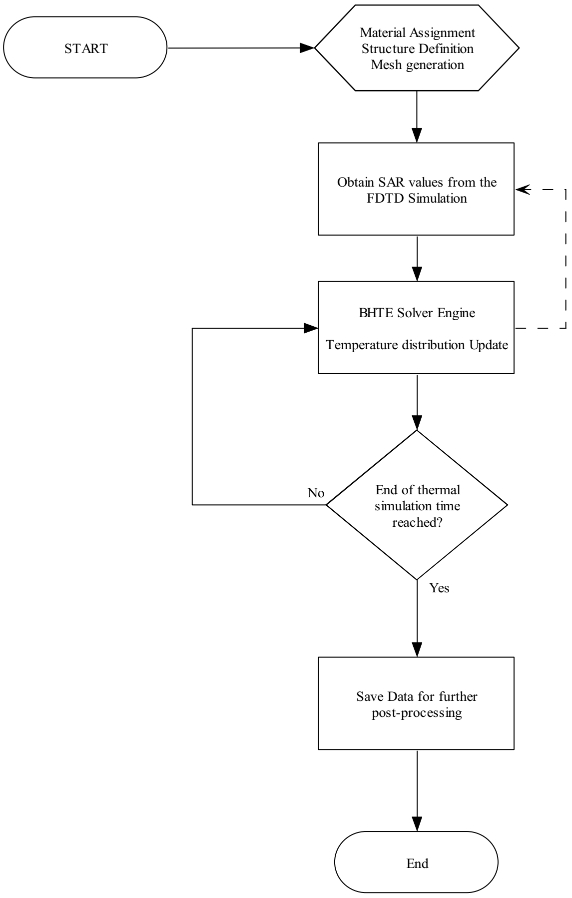
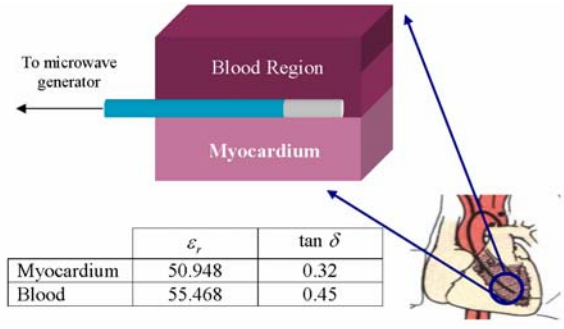


Figure 1: FDTD simulation flow chart.



	ε_r	tan δ
Myocardium	50.948	0.32
Blood	55.468	0.45

Figure 2: 3D-FDTD representation of the antenna within the myocardium.

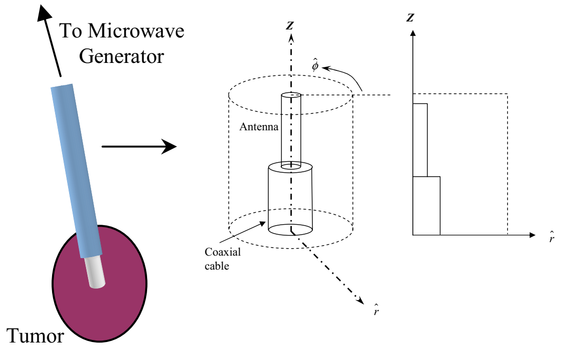


Figure 3: RS-FDTD representation of the antenna within the tissue.

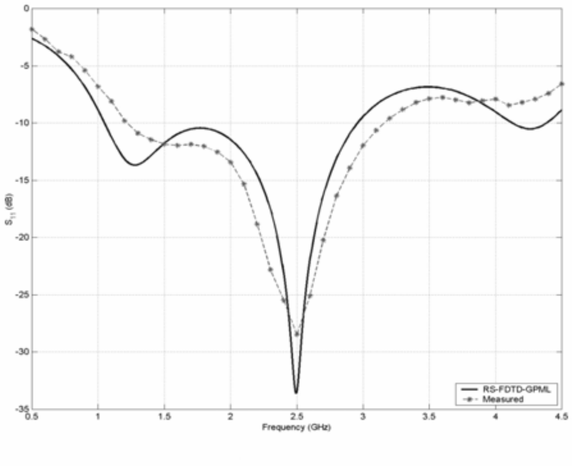


Figure 4: Measured and simulated reflection coefficients of ETW antenna in liquid phantom.

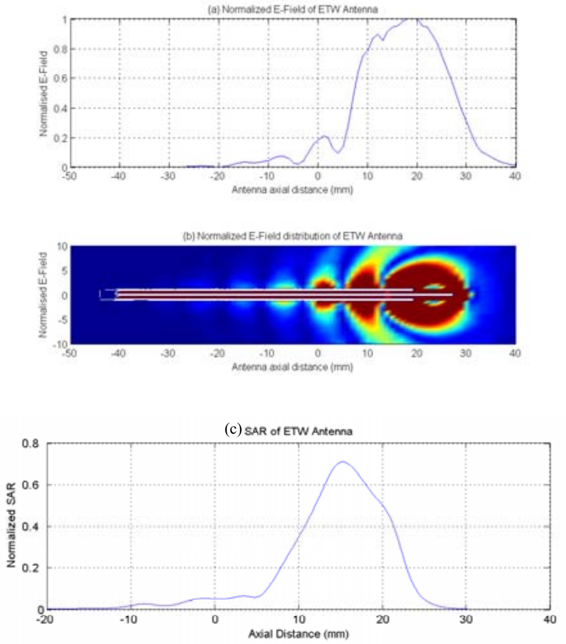


Figure 5: Normalized ***E***-field and SAR distribution of ETW antenna. (a) Normalized ***E***-field across the length of the coaxial cable and the antenna. (b) Spatial distribution of the Normalized ***E***-field**.** (c) Normalized SAR along the length of the antenna.

3. Results and Discussion

3.1 Cardiac Ablation

Cardiac rhythm disorders such as atrial fibrillation and flutter are conditions where the heart beats at an abnormally fast rhythm without external stimulant. If left untreated, these conditions can induce other cardiovascular problems such as stroke. Often these rhythm disorders are caused by tissue generating extra activation signals. Therefore, it is necessary to create linear thermal lesions on or around the affected tissues within the atrium to stop the generation of unnecessary activation signals.

The ETW antenna discussed in section 2 is used to create lesions on the bovine atrium. Fresh dissected bovine tissue is used to create lesions. Figure 6 shows the lesion created using the ETW antenna. Microwave power of 80 watts was applied for 30 seconds to the myocardium of the bovine heart. It can be seen that the lesion length is measured to be 25mm long which agrees well with the simulated length of the ***E***-field distribution shown in figure 5a. The inset showed in figure 6 indicates the depth of the lesion which has a measured depth of approximately 10 mm. This further shows the suitability of the ETW antenna in creating transmural lesions in the heart.

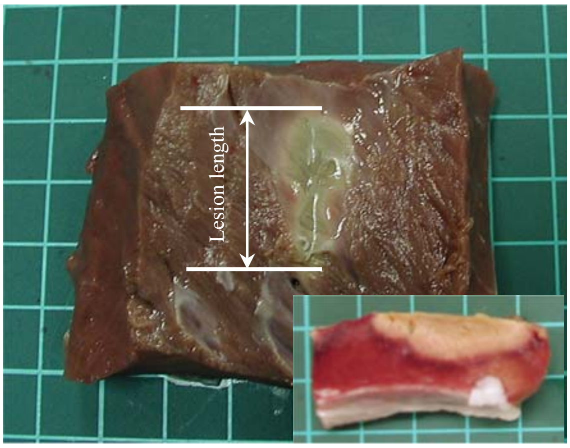


Figure 6: Lesion created using the ETW antenna on bovine heart tissue. The inset shows the depth of the lesion created indicating that transmural lesion has been achieved.

3.2 Ablation for Cancer Tumors

One of the criteria for the ablation of cancer tumors such as the hepatic tumor is the generation of large volume lesions. Hence the ***E***-field and SAR values produced by the microwave antenna for cancer tumor ablation should cover as much of the volume as possible [5].

We have modified the ETW antenna and optimized using RS-FDTD to obtain larger lesions. Figure 7 shows the thermal distribution generated by the modified ETW antenna as calculated from the predicted SAR values. From this figure, it can be seen that, the modified ETW antenna can deliver much wider lesion required to suit cancer ablation. It is clear that at a distance of 4 cm away from antenna, the tissue temperature is close to 60^{o}C so that tissue necrosis and coagulation can take place.

Figure 8 shows the lesion created inside a swine liver. The lesion is made using a single modified ETW antenna with 80 watts of applied power for 5 minutes. The diameter of the lesion is approximately 6cm and it can be seen that the modified ETW antenna produced a well demarcated lesion. It should be pointed out here that ETW antenna is highly amenable for array operation so as to further localize the volume lesions [4].

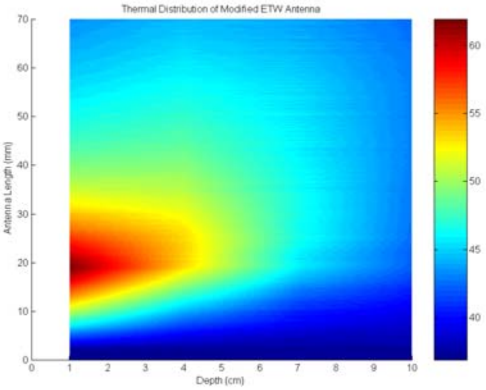


Figure 7: Simulated thermal distribution of the modified ETW antenna.

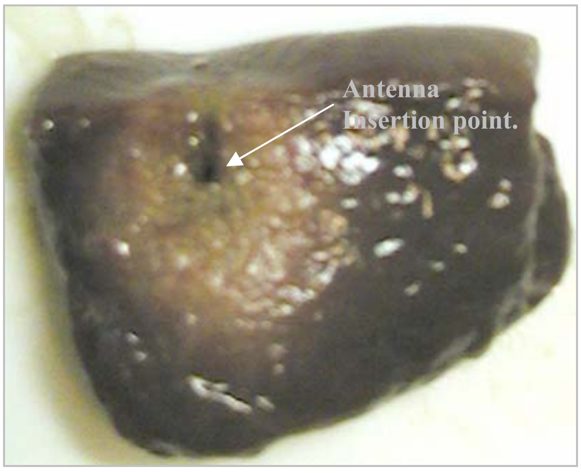


Figure 8: Lesion created using the swine liver tissue

4. Conclusions

In this paper, an overview of our work on the microwave ablation techniques for the cure of cardiac arrhythmias and thermal therapy for cancer is presented. We have shown that our miniaturized catheter antennas can create both linear lesions required for cardiac arrhythmias and large volume lesions required for cancer therapy. The simulation procedure based on RS-FDTD was found to be fast and accurate for the initial design and optimization of the microwave catheter antenna to obtain best performance.

In-vitro experiments were conducted and lesions were created on bovine hearts and swine liver. The lesions created by single antenna element on the bovine heart have confirmed the superior performance of our antennas. It is expected that an array of ETW antennas can be a suitable candidate for further localization of heating useful for coagulation and hyperthermia therapies.

Acknowledgement

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