NOVEL PARALLEL LOOP ANTENNA FOR CIRCUMFERENTIAL MICROWAVE ABLATION OF THE PULMONARY VEINS

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1. INTRODUCTION

Atrial fibrillation (AF) is a common arrhythmia associated with significant morbidity and mortality. Surgical procedures utilising extensive atrial incisions to localize the electrical signals that are responsible for causing arrhythmia have been, for many years, the only curative treatment [1]. A rapidly firing focus in or close to the pulmonary veins can be one of the causes of the arrhythmia in patients suffering paroxysmal AF [1]. Recently, reports of using radiofrequency and ultrasound energy for catheter pulmonary vein ablation have been proposed [1]. However, Pappone et. al.[1] found that it is extremely difficult in creating a continuous circumferential lesion on the pulmonary veins using radio frequency (RF) ablation. Similarly, inadequate heating was observed during ultrasound ablation [1].

In this paper we propose to use microwave energy operating at 2.45 GHz to overcome the limitations discussed by authors of [1]. Ablation using catheter based microwave antennas at microwave frequency have potential of overcoming some of the limitations experienced by RF. Currently catheter based microwave antennas are constructed using monopolar configurations [2]. The antennas proposed by Nevels et. al. [2] are designed to radiate in the normal mode generating well-defined heating pattern along the antenna length. Gu et. al [3] proposed a spiral antenna, which has a large radiating aperture that generated large semispherical lesions. A detailed search of literatures, indicate that, the microwave catheter antennas reported so far produce either linear lesions [2], wide aperture or spot lesions [3],[4].

Even though the above mentioned antennas produce reasonable lesions, they are not suited for ablation in the pulmonary vein, which requires a circumferential type lesion. In order to achieve a circumferential lesion, a continuous linear lesion along the circumference inside the pulmonary vein is required. Therefore, in this paper, a novel loop antenna that can fit inside the pulmonary vein to produce lesions along the circumference of the pulmonary vein is proposed. The feasibility of using such antenna in pulmonary vein ablation is demonstrated by comparing it with the existing antennas in phantom medium and *in vitro* experiments.

2. Material and Method

The loop antenna is constructed on a flexible coaxial cable with 2.13mm outer-conductor diameter and 0.5mm inner-conductor diameter. The Teflon that separates the inner and outer conductor has a 1.6mm diameter. Since the axis of the loop is parallel to the axis of the coaxial cable, this loop configuration is referred to as the parallel-loop (PL) antenna and it is shown in Figure 1. The inner, centre and outer circumferential length of the PL antenna are $1.4\lambda_g$, $1.7\lambda_g$, and $2.5\lambda_g$, respectively. The PL antenna is designed so that it can be easily inserted into the pulmonary vein via the atrium. Also shown in Figure 1a are the design parameters of the PL antenna such as the inner loop radius (I_r) and the outer loop radius (O_r). Also the tip of the loop antenna is properly terminated which allows for good impedance matching. One advantage of the parallel-loop antenna is that it allows the blood to flow through its loop axis and hence provide the necessary cooling on the inside of the loop where heating effect should be minimised.

Finite Difference Time Domain method is used to model the antenna in the pulmonary vein. HP8720A vector network analyser is used to obtain the dielectric constants of the pulmonary vein

tissue and blood. Fresh ovine hearts and blood are used in this study. The model consists of the antenna surrounded by blood inside the pulmonary vein. The three dimensional computational model is shown in Figure 1b. By assigning appropriate measured permittivity for blood and the pulmonary vein tissue, we can differentiate the pulmonary vein and the blood within the computation model. The simulations have been performed at 2.45 GHz.

The reflection coefficients of the parallel-loop antenna were also measured using the HP8720A vector network analyser. The measured reflection coefficient is compared with the predicted reflection coefficient calculated using the FDTD technique. The comparison of measured and predicted reflection coefficient is shown in Figure 2 and it can be seen that the results between the measurement and simulation agree reasonably well.
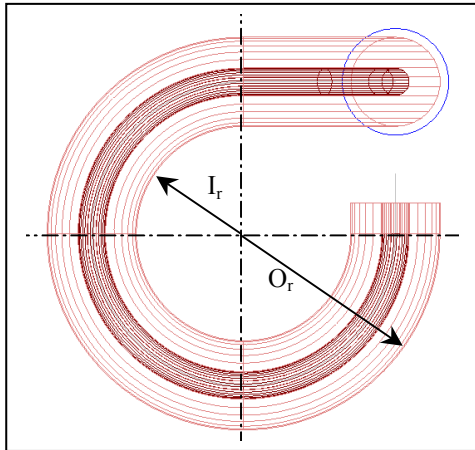

Figure 1a: CAD of the parallel loop antenna. I_r and O_r are the inner and outer loop radius respectively with the loop axis and coaxial cable axis coming out of the page.
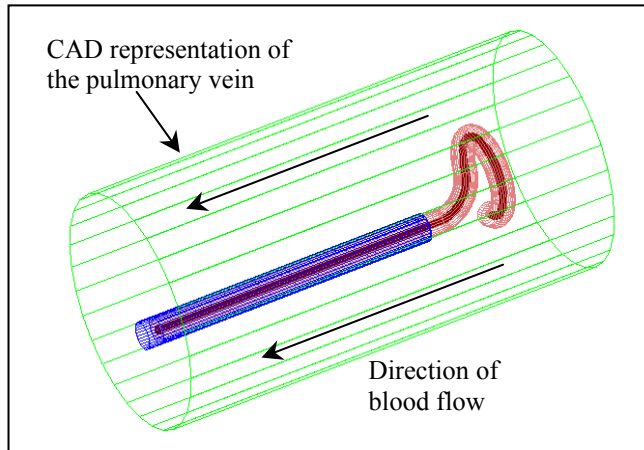

Figure 1b: CAD representation of the parallel loop antenna inside of the pulmonary vein. The arrows point to the direction fo blood flow.
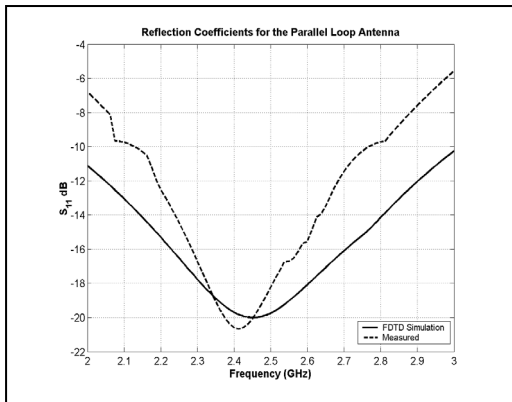

Figure 2: Measured and simulated reflection coefficients for the parallel loop antenna.
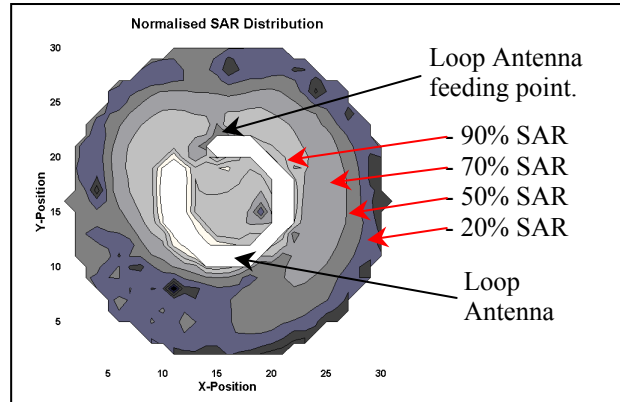

Figure 3: Normalised SAR distribution of the parallel loop antenna.

3. Results Analysis

The computed electric fields using the FDTD technique can be converted to the specific absorption rate (SAR) of the pulmonary vein tissue by using the following relationship:

$$SAR = \frac{\sigma}{2\rho}\left|E_{(x,y,z)total}\right|^2 \quad \text{W/kg} \tag{1}$$

Figure 3 shows the computed SAR distribution of the PL antenna. Note that within Figure 3, the blanked out section shows the geometry and the position of the PL antenna in FDTD computation domain. It is also seen that, except for the position direct opposite to the feed of the loop antenna, the SAR distribution is fairly uniformly distributed around the antenna. Due to the cylindrical nature of the pulmonary vein, the reduced SAR values at the position opposite to the feed of the antenna should

not cause problem as during the pulmonary vein ablation, the antenna can be rotated to give a more uniform SAR values around inner circumference of the pulmonary vein.

The computed SAR values are used to construct the three dimensional temperature distributions within the phantom tissue. The bioheat transfer equation (BHE) is used to describe the thermal characteristics [4] is given by:

$$\rho c \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) - W_b c_b (T - T_b) + Q_m + Q_{SAR} \qquad (2)$$

where ρ is the tissue density (1000 kg/m^3), c is the tissue specific heat (4000 J/kg ^{o}C), k is the tissue thermal conductivity (0.6 W/m ^{o}C), W_b is the blood perfusion, c_b is the blood specific heat, Q_m is the heat generated by the metabolism and Q_{SAR} is the heat generated by the microwave antenna due to the SAR. The blood and myocardium can be assumed homogeneous in a finite area and therefore the thermal conductivity of the blood and the myocardium tissue can be treated as constant [3]. The heat generated by the metabolism, Q_m, is negligible compared to the heat generated by the SAR and therefore it can be safely ignored. Since the ablation time is usually less than 180 seconds, in this paper, the thermal conductivity, k, is assumed to be constant with respect to time throughout the computation domain. The temperature rise due to the metabolism, Q_m, is considered negligible compared to the temperature due to microwave radiation, Q_{SAR}. Figure 4 shows the predicted temperature profile and the measured temperature profile during a forty-five seconds, 50 Watts ablation period. For the data on Figure 4, both the simulated and measured temperatures are made on the center of the loop. From Figures 4 it can be seen that the predicted temperature profile compares well with the measured ones.
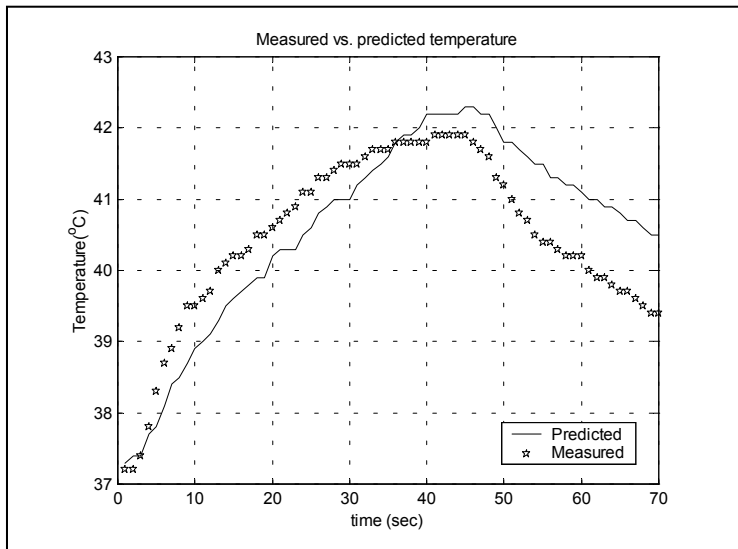

Figure 4: Temperature comparison for the predicted and measured temperature.

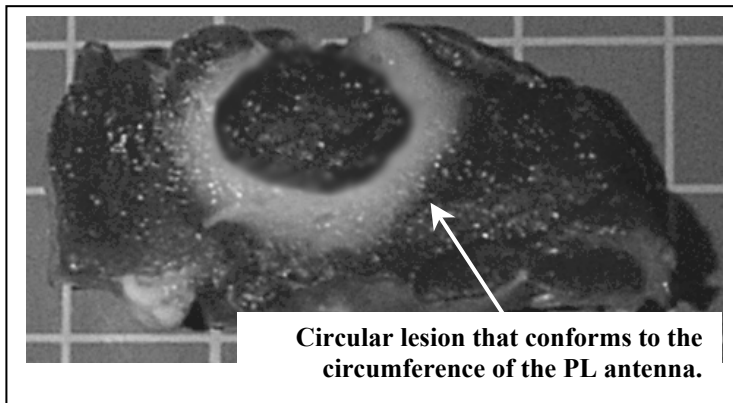**Circular lesion that conforms to the circumference of the PL antenna.**

Figure 5: Lesion created using PL antenna on myocardium.

Shown in Figure 5 is the lesion created using the PL antenna. In order to reflect its capability of generating circumferential lesions, the lesion has been produced on myocardium. The area inside the inner circumference of the PL antenna is constantly irrigated by blood and hence simulates the blood cooling effect. It is reflected on Figure 5 that the PL antenna does indeed produce lesions of circular-ring shape which is suitable for the ablation in the pulmonary vein.

Figure 6 shows the temperature distribution over 230 seconds at various point of the PL antenna. Thermocouples were fixed at the center of the loop, one fixed at 2mm away from the center of the loop, one fixed on the inner circumference of the loop and one fixed at the outer circumference of the loop between the loop antenna and the pulmonary tissue. Highest temperature was recorded by the thermocouple placed at the outer circumference of the loop adjacent to the pulmonary tissue. The point just on the surface of the inside circumference reached the same temperature as the point inside the pulmonary tissue during power

delivery, but it drops quickly when the power is switched off due to the blood flow within the vein. The temperatures at the center and 3mm away from the center of the PL antenna do not rise very high due to the high volume of blood flow. Experiments on fresh ovine hearts show that it is possible to create circumferential lesions inside the pulmonary vein using the PL antenna.
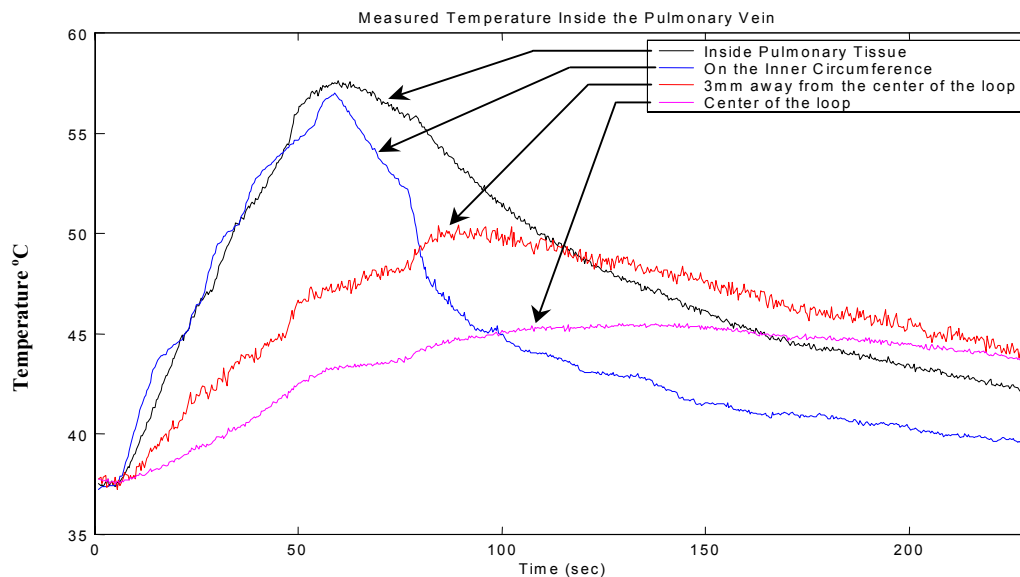

Figure 6: Measured temperature at various point of the parallel loop antenna.

4. Conclusion

A novel parallel loop (PL) antenna that is impedance matched to the pulmonary vein is proposed and analysed. Both the calculated and measured SAR and temperature distributions have shown the capability of the PL antenna in creating linear circumferential lesions around the pulmonary vein. Overall, the proposed PL antenna is capable of generating temperatures of greater than 55 degrees required for irreversible lesion formation in a very short period of time.

Acknowledgment

REFERENCES

[1]. C. Pappone, S. Rosanio, G. Oreto, M. Tocchi, F. Gugliotta , G. Vicedomini, A. Salvati, C. Dicandia, P. Mazzone, V. Santinelli, S. Gulletta, and S. Chierchia, "Circumferential Radiofrequency Ablation of Pulmonary Vein Ostia: A New Anatomic Approach for Curing Atrial Fibrillation", Circulation, pp. 2619-2627, Nov. 2001.

[2]. R. D. Nevels, D. Arndt, G. W. Raffoul, J. R. Carl, and A. Pacifico, "Microwave Catheter Design", *IEEE Trans. BME, Vol. 45, No7. Pp885-890, July 1998.*

[3]. Gu, C. M. Rappaport, P. J. Wang and B. A. Vanderbrink, "Development and Experimental Verification of the Wide-Aperture Catheter-Based Microwave Cardiac Ablation Antenna", *IEEE Trans. Microwave Theory Tech.* vol 48, No. 11, pp. 1892-1900, December 2000.

[4]. James C. Lin and Yu-Jin Wang, "A Catheter Antenna for Percutaneous Microwave Therapy", *Microwave and Optical Technology Letters*, Vol. 8, No.2, February 1995.

[5]. K. Saito and K. Ito, "A Study of the SAR Distribution of a Coaxial-Slot Antenna for Interstitial Microwave Hyperthermia by the FDTD Method", *Electronics and Communications in Japan,* Vol. 84, Nov. 2001.