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Optimization of low-cost needle microwave applicators for cancer therapy

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Abstract

In this paper, the design and optimization of a low-cost needle microwave applicator for cancer therapy is illustrated. An adequately sized coaxial antenna inserted into a thin hypodermic needle, is optimized in the Industrial, Scientific and Medical frequency band (ISM) at $f = 2.45\ GHz$. An extensive feasibility investigation is performed in order to obtain an efficient, mini-invasive and low-cost microwave medical device. Several technical solutions are explored and the optimization of a number of needle microwave applicators is performed. The performance of the applicators is evaluated in terms of antenna impedance matching, specific absorption rate (SAR), temperature distribution, and ablation zone sizes. After a comparison, a 14 gauge (14G) and a 16 gauge (16G) prototypes are fabricated and characterized.

1 Introduction

The antennas can be employed in biomedical field with the aim to transfer the electromagnetic (EM) energy to the human body for several diagnostic and therapeutic applications. In particular, they have recently attracted a lot of interest for the hyperthermic treatment of cancer [1-6]. In this therapy the antennas are used in direct contact with the specific biological target, in which the local absorption of EM energy causes high temperature such as to destroy the tumoral cells.

In this work, the optimization of low-cost microwave applicator for cancer therapy is performed. Various technical solutions are explored in order to obtain a good trade-off between: i) good microwave absorption by the tumour; ii) small applicator sizes for mini-invasive therapy; iii) low-cost and easy fabrication process; iv) localized thermal lesion area close around the cancer. A coaxial antenna operating at the $f = 2.45\ GHz$ frequency, inserted into a biopsy needle for a hyperthermic interstitial treatment of hepatic tumour, is considered. The design and optimization have required a multiphysical approach, the solution of the EM and thermal problems by Maxwell equations and bio-heat equation (BHE) have been needed. The design is performed by employing the CST Microwave Studio© software; the modulus of the scattering parameter S_{11}, the SAR and temperature distributions in the biological model, the shape and axial dimensions of the thermal ablation zone are simulated as a function of the ablation duration time and for several values of the input power. Two prototypes are fabricated and characterized. The experimental results are in good agreement with simulations.

2 Design and optimization

The needle microwave applicator investigated is a triaxial antenna [2-3] and is schematically composed by three sections: i) the radiating section, i.e. a coaxial antenna that terminated with a metallic tip; ii) the insulating section, realized with biocompatible dielectric material that embedded the radiating section; and iii) a hypodermic tube for biopsy, in which the antenna is fitted and that allows the percutaneous insertion of the antenna into the biological tissue. Figure 1 shows the lay-out of the needle microwave applicator for cancer therapy. The design and optimization have been performed by EM thermal simulations. The first goal is the achievement of a good impedance matching of the antenna with the biological load in order to optimize EM energy delivery from the microwave source to the tumour. The field distribution into the biological tissue has been evaluated by simulating the SAR. The electrical characteristics of the liver and the tumour have been considered for a correct evaluation of the effects of the interaction between EM field and biological tissue.

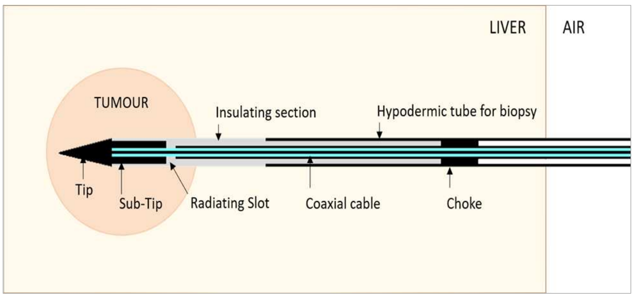

Figure 1. Lay-out of the needle microwave applicator for cancer therapy.

Subsequently, the thermal distributions inside the biological tissue have been evaluated by using the BHE [7], taking into account the human tissues thermal properties and considering such as reference temperature the normal internal body temperature of $T_r = 37°C$. Also, the human blood perfusion coefficients are considered to perform *in-vivo* simulations. In all simulations, the applicator irradiates into a cubic model of hepatic tissue in which a spherical cancer mass is centrally positioned. Dielectric and physical properties of liver and cancer have been taken from the literature [6, 8].
Starting from a monopole antenna, the radiating system of the applicator has been designed and optimized in the Industrial, Scientific and Medical frequency band (ISM). Different geometries are investigated: i) by introducing a choke [5], that allows to enhance the impedance antenna matching; ii) by adding a cylindrical metallic element (called sub-tip in Figure 1) that extend the tip inside the insulating section and has allowed the tuning of the resonance frequency; iii) by varying length and number of the radiating slots. With the aim to design a mini-invasive applicator, the cross section of the antenna has been miniaturized to fit into a 14G ($1.74 \div 2.20\ mm$) and a 16G ($1.39 \div 1.69\ mm$) hypodermic tube. Figure 2 shows the modulus of the scattering parameter S_{11} as a function of the frequency, simulated for different lengths of the choke L_{choke} of the 16 G needle microwave applicator, $|S_{11}|$ = -26.5 dB at f = 2.45 GHz for $L_{choke} = 28\ mm$.
An almost spherical thermal lesion close to the antenna radiation section, has required more elaborate geometry and more complicate fabrication process. Innovative 3D additive printing techniques have been considered for the manufacturing of the insulating section, in order to reduce costs and simplify the fabrication process.

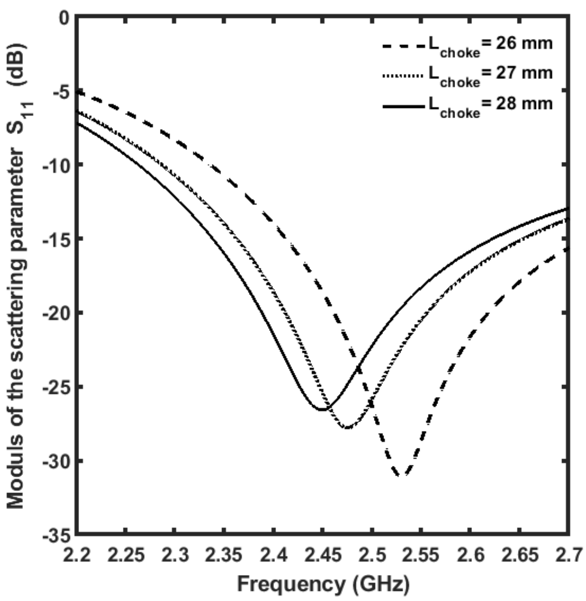

Figure 2. Modulus of the scattering parameter S_{11} as a function of frequency simulated for different lengths of the choke $\boldsymbol{L_{choke}}$ of the 16 G needle microwave applicator.

The impact of electrical and thermal properties variations of the insulating section is investigated. A photo-reactive polymer for additive manufacturing, used for medical applications, has been considered for the insulating section of the 14G applicator. The simulations proved the possibility of designing and manufacturing an ad-hoc insulating section with 3D printing technique in order to simplify the manufacturing process.
The thermal simulations have been performed considering a cooling circuit inside the applicator, able to guarantee, far from the radiant section, the maintenance of a stable temperature within the limits set by the therapeutic indications, in order to avoid damage to the healthy tissues. The effects of the cooling circuit on the applicator performances are evaluated. Simulations of the 14G and 16G applicators with and without the cooling circuit have highlighted better results in the case of the version with cooling, in which the typical comet tail profile of the thermal lesion results reduced. Moreover, a better control of the applicator performance during the therapeutic treatment could be possible with a real time temperature monitoring system integrated with the applicator, e.g. an optical fiber temperature sensor [9].
In order to compare the simulation results with experimental one, *ex-vivo* thermal simulations are performed by neglecting the blood perfusion coefficients and metabolic rate. Figure 3 shows the longitudinal section of the temperature distribution into the hepatic tissue simulated after an ablation duration time of $t = 600\ s$. The *ex-vivo* simulation are performed with a power supply of $P = 20\ W$ with the 16G needle microwave applicator positioned into a spherical tumoral mass (the black circle in Figure 3). A thermal lesion at $50°C$ of $34\ mm \times 41\ mm$ axial sizes is simulated.
The 14G and 16G prototypes have been fabricated and characterized. Figure 4 shows the experiment pertaining to a thermal lesion of bovine *ex-vivo* liver, produced with the 16G prototype by using a power supply of $P = 20\ W$ for $t = 600\ s$. The thermal lesion (tissue discolored zone in Figure 4) of $34\ mm \times 40\ mm$ axial sizes is measured.

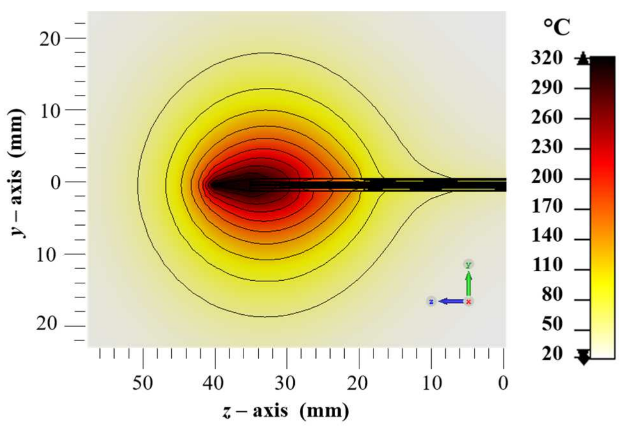

Figure 3. Longitudinal section of the temperature distribution into the hepatic tissue simulated with a power supply of P = 20 W, after an ablation duration time of $t = 600\ s$**.** 16G needle microwave applicator.

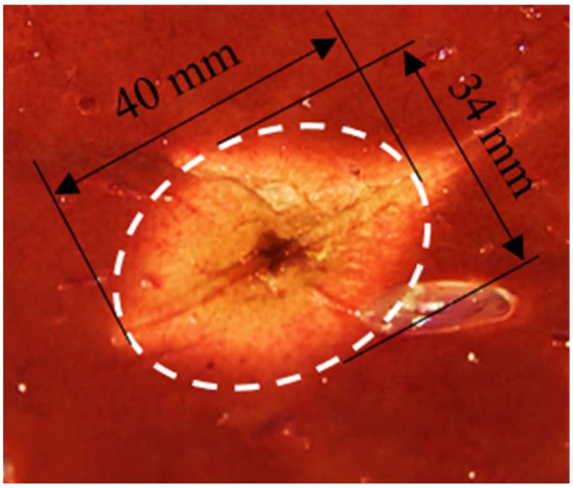

Figure 4. Thermal lesion bovine ex-vivo liver produced using a power supply of $P = 20\,W$ for $t = 600\,s$. 16G needle microwave applicator prototype.

3 Conclusion

Several approaches for the optimization and fabrication of low-cost needle microwave applicators for cancer therapy are investigated. Electromagnetic and thermal simulations are performed; the thermal lesion shape dimensions are evaluated as a function of the ablation duration time and for several values of the input power. Two prototypes of 14 gauge and 16 gauge have been designed, optimized, fabricated, and characterized. The experimental results are in good agreements with simulations. The design of a temperature monitoring system based on optical fiber integrated with the microwave applicator is considered for future developments.

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