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Theoretical and experimental study on RF tumor ablation with internally cooled electrodes: When does the roll-off occur?

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Abstract— **The Cool-tip is one of the most widely employed electrodes in radiofrequency (RF) ablation (RFA) of hepatic tumors. This electrode creates reliable geometry and coagulation zones. Despite the advantages of this electrode, during the ablation is produced a phenomenon called roll-off in which impedance increases, energy deposition completely stops and the lesion size cannot be increased. Consequently, the thermal lesion size is smaller and the tumors which can be ablated are smaller too. In this research we studied theoretical and experimentally the electrical-thermal performance of the Cool-tip electrode during RFA of hepatic tissue. Mainly, we were interested in the occurrence of the roll-off and its relationship with the tissue temperatures around the electrode. The theoretical model included the vaporization of the tissue and the variation of the thermal and electrical conductivities with temperature. The model was solved numerically using COMSOL Multiphysics software. For the experimental part we conducted a study in ex vivo liver tissue. The experimental and theoretical results showed that the roll-off is totally related when temperatures around 100ºC surrounds the tissue close to the center of the Cool-tip. The knowledge of this fact brings a powerful tool to analyze alternative methods or techniques to avoid the roll-off.**

I. INTRODUCTION

Radiofrequency (RF) ablation (RFA) of liver tumors is a minimally invasive procedure that allows the treatment of primary and metastatic liver tumors [1], [2]. This technique uses RF current (≈500 kHz) to produce a thermal lesion to destroy a liver tumor. The electrical current is delivered to the tissue through a small active electrode placed in the tumor, and a large dispersive electrode located on the patient's back. One of the commercially available active electrodes is the Cooltip® (Valleylab, Boulder, CO, USA). This electrode creates thermal coagulation areas with predictable geometry [3]-[5]. It consists of an internally cooled electrode, i.e. a cold liquid is flowing inside of the electrode to keep the surface of the electrode cool in order to prevent the surrounding tissue from charring. Despite that it has been broadly employed the relationship between temperature distribution in the tissue and the impedance progress has not been characterized in detail yet. Our hypothesis is as follows: The thermal lesion begins in the tissue close to the edges of the active electrode, i.e. at the tip and the proximal edge. Then, the lesion size increases toward the center by thermal conduction and this is associated with a slow impedance decrease. In particular, the most charring zone is 1-2 mm away from electrode surface. During its performance, it is usual to observe a sudden increase in the electrical impedance measured between active and dispersive electrode, even above the initial impedance, and the consequent decrease in electrical power. This phenomenon is called roll-off, and has been traditionally associated to high temperatures (≈100ºC) reached in the tissue, and strongly charred tissue. Our hypothesis is that when the charring reaches the middle zone of the electrode the roll-off occurs. Consequently, our aim was to demonstrate theoretical and experimentally this hypothesis.

II. METHODS

A. Theoretical model

The problem is based on a coupled electric-thermal problem, which was solved numerically using the Finite Element Method (FEM) by means of the software COMSOL Multiphysics (Stockholm, Sweden).

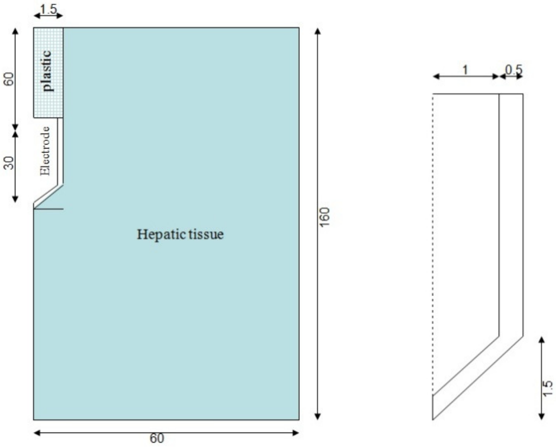

Fig. 1. Geometry and dimensions (in mm) of the theoretical model.

The geometry and the dimensions of the theoretical model we proposed are shown in Fig. 1. Due to the geometry, the problem presented axial symmetry and a 2D analysis could be conducted. The model included three different materials:

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The plastic electrode handle, the electrode Cool-tip and the liver. The dispersive electrode was modeled as an electrical condition on boundaries far from the active electrode. The parameters used for the modeling are shown in Table 1. The electrical and thermal conductivity of the liver were piecewise functions. For the thermal conductivity (k) we considered a linear growing of 0.159%/ºC until 100ºC and after this temperature k was constant. In the case of the electrical conductivity (σ) grew exponentially 1.5%/ºC until 100ºC, between 100 and 105ºC was constant and after that σ decreased linearly 2 orders during five degrees [9]. Analytically, the piecewise functions were defined using Heaviside function that in COMSOL was substituted by the smoothed function *flc2hs* [6].

TABLE I

CHARACTERISTICS OF THE MATERIALS AND PARAMETERS OF THE THEORETICAL MODEL

	Constant	Value	Ref
σ_e	Electrode electrical conductivity	7.4e6 S/m	[9]
k_e	Electrode thermal conductivity	15 W/m·K	
ρ_e	Electrode density	8000 kg/m^3	
c_e	Electrode specific heat	480 J/kg·K	
σ_p	Plastic electrical conductivity	1e-5 S/m	
k_p	Plastic thermal conductivity	0.026 W/m·K	
ρ_p	Plastic density	70 kg/m^3	
c_p	Plastic specific heat	1045 J/kg·K	
ρ_{tl}	Tissue density in liquid phase	1080 kg/m^3	[6]
ρ_{tg}	Tissue density in gas phase	370.44 kg/m^3	
h_{lg}	Latent heat	1.5368e6 J/kg	
c_{tl}	Tissue specific heat in liquid phase	3455 J/kg·K	
c_{tg}	Tissue specific heat in gas phase	2155.92 J/kg·K	
ρ_{tc}	Tissue density in the change of phase	725.22 kg/m^3	*
h	Convection coefficient	2670 W/m^{2}K	[5]
$Tref$	Cooling temperature	5ºC	
V_p	Punctual electrical source	80 V	#
T_a	Ambient temperature	26.5ºC	

*Mean value between the tissue density in liquid and gas phase. # Values obtained from the experimental study.

As we have mentioned below, from a mathematical point of view the model was based on a coupled electric-thermal problem. The governing equation for the thermal problem for plastic and electrode is the classic heat conduction equation:

$$\rho_i c_i \frac{\partial T}{\partial t} = \nabla(k_i \nabla T) + q + Q_p + Q_m \quad i = e, p \quad (1)$$

In the case of the hepatic tissue we wanted to take into account the tissue vaporization. According to [8], the vaporization phenomenon can be modeled using the enthalpy method in this way:

$$\begin{aligned} 0 \le T \le 100^{\circ} C & \quad \rho_{tl} c_{tl} \frac{\partial T}{\partial t} = \nabla(k\, \nabla T) + q \\ 100^{\circ} C \le T \le 105^{\circ} C & \quad \rho_{tc} h_{\lg} \frac{\partial T}{\partial t} = \nabla(k\, \nabla T) + q \quad (2) \\ T > 105^{\circ} C & \quad \rho_{tg} c_{tg} \frac{\partial T}{\partial t} = \nabla(k\, \nabla T) + q \end{aligned}$$

where the products ρ_{tl} c_{tl}, ρ_{tc} h_{lg}, ρ_{tg} c_{tg} are related with the volumetric enthalpy for the liquid liver, the change of phase and the phase gas of the liver, respectively [10]. T is the temperature, t is the time, ρ is the density, c the is specific heat, k is the thermal conductivity, q is the heat source produced by RF power, Q_p is the heat loss from blood perfusion and Q_m is metabolic heat generation. Equation (1) was only used for the materials of the model which did not suffer vaporization; in this way the subscript i referred to the electrode (e) and the plastic (p). Q_m are insignificant in the RF of the liver and thus was not considered. Since the experimental study was ex-vivo Q_p was not also considered. The heat source q (Joule losses) is given by q=JE, where J is the current density and E is the electric field strength and they were obtained from the electrical problem. The governing equation for the electrical problem is the Laplace equation ∇^2V=0, where V is the voltage. The electric field is calculated by means of E = -∇V and J using Ohm law (J= σE). We used a quasi-static approach due to the frequencies used in RF (≈500 kHz) and for the geometric area of interest the tissues can be considered as purely resistive [7]. The air circulating inside the electrode produce a cooling effect modeled by means of a thermal convection coefficient h. The mesh size was of 0.66 mm around the electrode-tissue interface where the highest gradient was expected and the automatic size of mesh which COMSOL provides for the rest of the geometry. For the time-step in solver we used smaller times at the beginning of the heating process where changes in temperature and voltage were produced more suddenly. This is a possibility that COMSOL offers selecting the option *Times steps from solver/strict* at the Solver Parameters menu.

B. *Experimental set up*

In order to measure the temperature in three concrete locations, we used a temperature probe with embedded small sensors (usually thermocouple) to record the temperature at the electrode surface. The distribution between them was a distance of 1 cm. Fig. 2 shows the multi-thermocouples probe and the electrode tip. T1, T2 and T3 were the positions of the sensors from the electrode tip, i.e. 0.5, 1.5 and 2.5 mm respectively. These positions were selected to obtain the evolution of the charring, i.e. the temperatures in the tissue surrounding the electrode tip. Therefore, we could demonstrate when the roll-off occurs.

The multi-thermocouples probe was a flexible Teflon-coated 17-gauge of diameter IT Series T-type (Physitemp Instruments, Crifton, NY, USA). We combined the Cool-tip and the multi-thermocouples probe to register the temperature in the tissue. For that, we used a nylon thread of small dimensions (<1 mm) to tie the multi-thermocouples probe to the electrode. This knot was located outside of the electrode tip (see Fig. 2). This allowed us to put accurately the sensors with respect to the center of the electrode tip. The experimental study was conducted in ex vivo liver tissue. We acquired a piece of fresh bovine liver of 3.5 kg and we positioned the liver in a container. We employed a Cool-tip electrode of 3 cm, which is currently used in clinical practice and we used a dispersive electrode of 600 cm^2 of area.

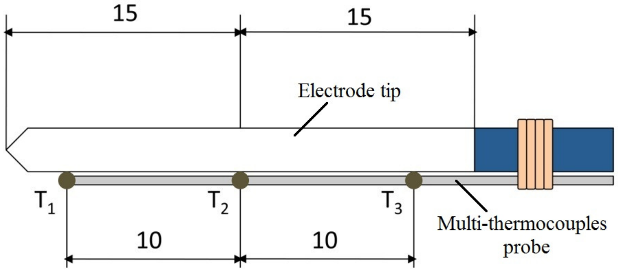

Fig. 2. Combination of the Cool-tip and the multi-thermocouples probe. Measurements (in *mm*).

The RF energy was administrated by a RF generator CC-1 (Radionics, Burlington, MA). T1, T2 and T3 were recorded in the tissue surrounding the electrode surface tip by a multi-thermocouples probe. The register of the temperature was made by a data acquisition card ThermesUSB (Physitemp Instruments, Crifton, NY, USA) and the data file was generated by 9.0 DASYLab software (Measurement Computing, Norton, MA).

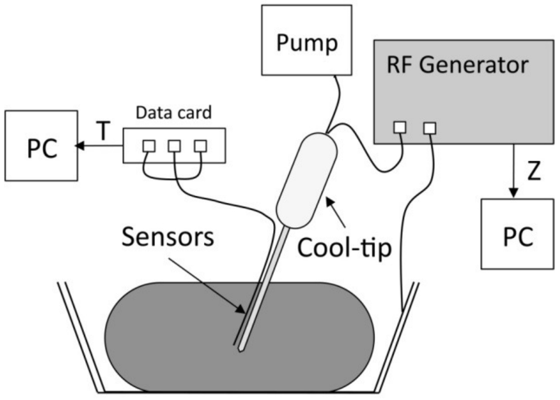

Fig. 3. Experimental setup to register the temperature measured in the tissue and the impedance progress.

Moreover, the tissue impedance was recorded between the active electrode and the dispersive electrode. The impedance progress was registered by another data acquisition card and the data file was generated by Agilent VEE software (Agilent Technologies, Santa Clara, CA). The sampling frequency used in both systems was 0.1 Hz. A peristaltic pump was used to cool the electrode tip with a tank with cold water (5ºC). The water flow rate was 45 mL/min. Fig. 3 shows the experimental set up described above. The ambient temperature was 26ºC. We used a voltage of 80 V. We recorded the variables (temperature and impedance) until the roll-off occurred.

III. RESULTS

A. Theoretical results

In order to obtain theoretically the same impedance than experiments we adjusted the initial tissue electrical conductivity. Fig. 4 shows the progress of the theoretical impedance measured between the Cool-tip (active electrode) and the dispersive electrode. We observed that initially the impedance was ≈ 100 Ω, and decreased until ≈ 65 Ω before roll-off. Fig. 5 shows the theoretical temperature distributions in the tissue around the electrode (above) and the progress of the 100ºC isotherm in the same zone (below) at five specific times. Both results allows to validate the hypothesys, i.e, the occurrence of the roll-off corresponds closely with the time when temperature of 100ºC reaches the middle zone.

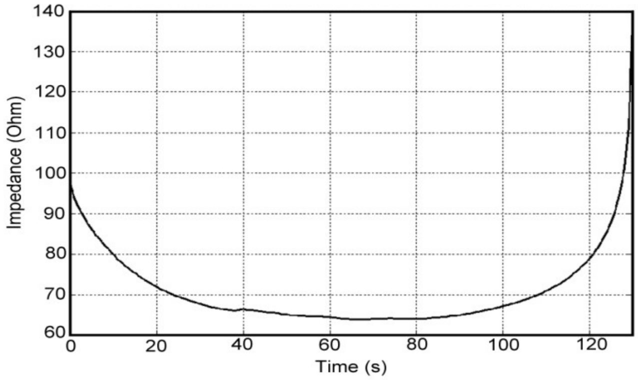

Fig. 4. Progress of the computed impedance between the Cool-tip (active electrode) and dispersive electrode.

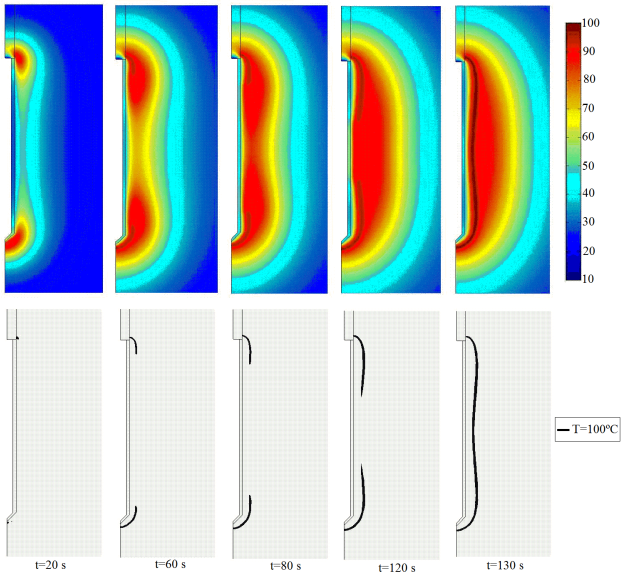

Fig. 5. Theoretical temperature distributions in the tissue around the electrode (above) and progress of the 100ºC isotherm in the same zone (below)

B. Experimental results

We used the mean of the 20 ablations. The average time needed for a roll-off to occur was 80 s. The initial impedance was 98.8 ± 5.6 Ω. Fig. 6 shows the temperature mean progress at the three locations T1, T2 and T3 (Fig. 2).

We observed that while T1 and T3 increased rapidly up to temperatures of 100ºC (at ≈20 and 40 s respectively), T2 increased more slowly; in particular, it stabilized around 50 s with a temperature value of ≈ 98ºC. Fig. 7 shows the mean impedance evolution. The sudden increase in impedance occurred at 50 s approximately when T2 was stabilized, which validates the hypothesis from the experimental point of view.

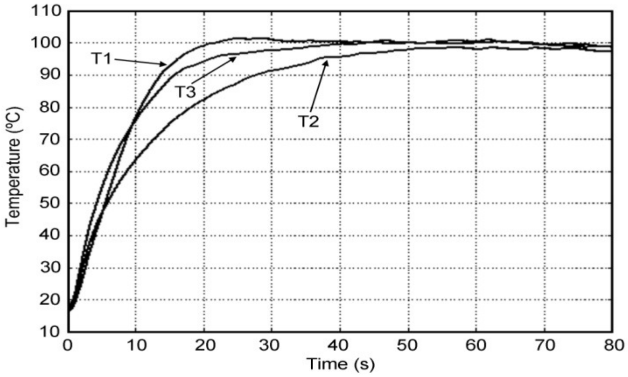

Fig. 6. Temperature mean progress of the temperature sensors placed in the tissue surrounding of the surface electrode tip. T1, T2 and T3 were the positions of the sensors from the electrode tip, i.e. 0.5, 1.5 and 2.5 mm respectively (n = 20).

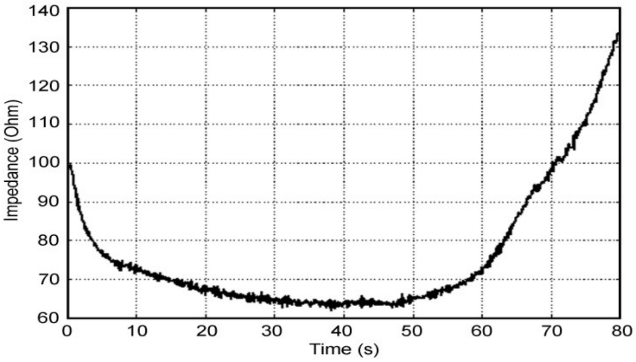

Fig. 7. Mean progress of the impedance measured between the Cool-tip (active electrode) and dispersive electrode (n=20).

IV. DISCUSSION AND CONCLUSION

Our aim was to demonstrate theoretical and experimentally that when the temperature value measured at the center of the active electrode is about 100ºC, the impedance rises rapidly producing a roll-off. Both theoretical and experimental results suggest that the hypothesis about the relationship between impedance and charring distribution is true.

Although in experimental and theoretical studies we obtained similar results in the occurrence of roll-off and its relationship with temperature, we observed that the roll-off is not produced at the same time. In the experimental study the average time needed for a roll-off to occur was 80 s (Fig. 7) and theoretical results showed that it is produced at ≈ 125 s (Fig. 4).These differences were also apparent in experimental and theoretical tissue temperatures (Figs. 5 and 6, respectively). We think that it could be due to the function considered for the electrical conductivity in theoretical modeling. Further studies in order to check the effect in the assumption of the electrical conductivity and other tissue variables, as the thermal conductivity and the specific heat, could validate this hypothesis. In addition the results of this study could explain the results found by using an electrode developed by our group, which is an internally cooled electrode combined with a saline infusion exactly in the middle zone of the electrode [11]. Despite of this disappointing between theoretical and experimental results, both allow us to demonstrate our hypothesis. The results of the theoretical and experimental study suggest that the roll-off is closely related with the time when the charring reaches the middle zone of the electrode, i.e. temperatures around 100ºC

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