Optimizing the electrothermal dynamics in Radio Frequency Ablation treatments

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Abstract — Clinical treatment of illness such as some forms of epathocarcinoma makes use, in several cases, of thermal ablation induced by radio frequency currents injected into the tumor volume. To this purpose a sophisticated probe is inserted into the tumor and a return path is provided by applying a plate-electrode on the patient's skin. In this paper a new mathematical formulation of the problem is provided in terms of possible degrees of freedom, bounds and goals first and secondly dynamic programming algorithms are proposed in order to optimize the electric power deposition on the living tissues.

I. INTRODUCTION

Medical treatments are characterized by complex dynamics, involving physical and/or chemical interactions among instrumentation and living tissues. Mathematical modeling of such processes is often very challenging, and, in addiction, reliability and accuracy requirements clashes with the high uncertainty affecting the data to be processed while the results of any computation have to be simple and definite enough to be of practical use for any medical specialist.

In this paper, the Radio Frequency Ablation (RFA) treatment for some forms of epathic tumors is considered as a possible application of treatment improvements through numerical modeling. Epathocarcinoma in certain cases, indeed, are not surgically removed, but ablated by exploiting Joule heating caused by RF current flowing into the tumor volume. A RFA session requires the laparoscopical or percutaneous insertion of a probe into the patient's body, the positioning of the probe tip into the tumor, the application of a single return electrode usually on the back of the patient [1], and the injection of RF current through a specific power supply system. The probe tip is a rather sophisticated mechanical structure, endowed with a cooling water flow and metallic retractable prongs in electric contact with the ill tissue. [2]. The Ohmic power deposition causes then a local temperature rise, depending on current density map and on tissues conductivity. If a cell temperature exceeds 45–50 °C, the denaturation of intracellular proteins and destruction of cell membranes occurs, whereas at about 60°C the cell death is assumed instantaneous. A quantitative measurement of the lesion undergone by a certain volume of tissue is provided by *Arrhenius damage index* [3].

The current density map can be changed, in principle, by varying a number of parameters. Preliminary optimal planning of the treatment, i.e. of the shape and volume of the ablated region has been proposed [3] based on the optimal positioning of the probe. The use of multiple return electrodes has been recently proposed [4] with the aim to optimize the power delivered to the tumor volume and to prevent healthy tissues from damage. Recently the authors, finally, introduced the dynamic optimization of the current patterns by applying the classical Jacobi-Bellman theory [5, 6].

In this paper, an example of the improvement following a more effective choice of voltage on the various prongs of the probe tip will be presented. The possible degrees of freedom to be exploited in the optimization will be presented with particular reference to the simultaneous optimization of the voltage on the prongs tip and on multiple back plates.

II. ELECTROTEHRMAL MODEL OUTLINE

The optimization of the RFA treatment requires (i) a *forward model* able to predict the local temperature rise in the tissues as well as the consequent damage of the tissue itself, and (ii) an *optimization strategy* to look for the optimal choice of control parameters. In this section just the forward problem is briefly sketched, but due to the lack of room a more detailed formulation of both forward and optimization problems is deferred to the full paper. In order to allow an effective analysis of the impact of geometric changes on the optimization results (see Fig. 1) in this paper a fully parametric domain Λ is considered. The main simplifying assumptions concern that only three different tissues properties have been considered, denoted in the following by "liver", "torso" and "tumour".

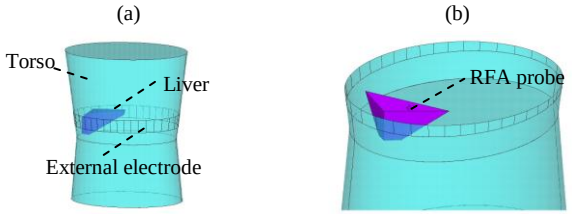

Fig. 1. Solution domain (a) and cross section (b) highlighting the RFA probe schematization

The mathematical model of the forward problem falls in the class of coupled electro-thermal problem. In the Electromagnetic sub-problem, the Ohmic power density distribution is calculated for known (electrical) tissues properties and RF current pattern applied on the external electrodes, under the electro-quasi-static assumption. The solution of the electromagnetic subproblem depends on the tissue temperature map since conductivity is assumed to be temperature-dependent. In the thermal subproblem the temperature is calculated from the Pennes bioheat equation [1], taking into account the contribution of the Ohmic power density, acting as a heat source. The tissues perfusion acts as a heat sink (metabolic sources are

neglected), and the natural convection as well as the internal on the domain boundary and internal probe cooling are both taken into account.

The overall electro-thermal model is non-linear because the temperature variation of electrical tissues properties is taken into account. The thermal problem is also non linear because the perfusion contribution to the source term is a function of the temperature. Finally, as a post processing of the temperature, an estimate of the survival fraction of the cells is provided by applying the *Arrhenius* model [3].

III. PRELIMINARY RESULTS

In this section, some preliminary remarks are presented and discussed. A Finite Elements (FE) model of the simplified human torso introduced in Sect. II has been meshed using 7579 3D linear elements, and a commercial FE package has been used to solve the coupled electro-thermal problem above described. The degrees of freedom considered in this digest to improve the RFA treatment are the voltages of each prong of the internal probe, assumed independent each from the others.

Since prongs are equipotential, an almost equipotential region appears into the tumor volume near the tines (see fig. 2). In this paper A finer control of the local current field is proposed , useful for larger tumor volumes for which the chances of unsuccessful outcome are higher; the new scheme is based on the independent control of the voltages of the various tines. As an example 10, 20 and -10 voltages are applied in three of the tines with respect to the fourth one, and resulting current density map is compared to the map obtained when all prongs are at the same potential (see fig. 3). In this case local current paths are obtained between couples of prongs. The ~~expected~~ advantage is to gain the opportunity to perform a finer control of shape and size of the ablated volume surrounding the RF probe.

IV. CONCLUSION

The paper assesses the introduction of possible degrees of freedom in an RFA treatment of liver tumor. A mathematical model describing electrothermal dynamics is used, able to describe also cellular death rate, thanks to Arrenhius equation. A 3D FE mode is used to solve the forward problem. Preliminary numerical simulations to analyze the impact of additional degrees of freedom in RF ablation provide encouraging results, and a more complete discussion on the parameters to be optimized will be presented. In addiction dynamic programming methods will be applied to perform the optimization itself.

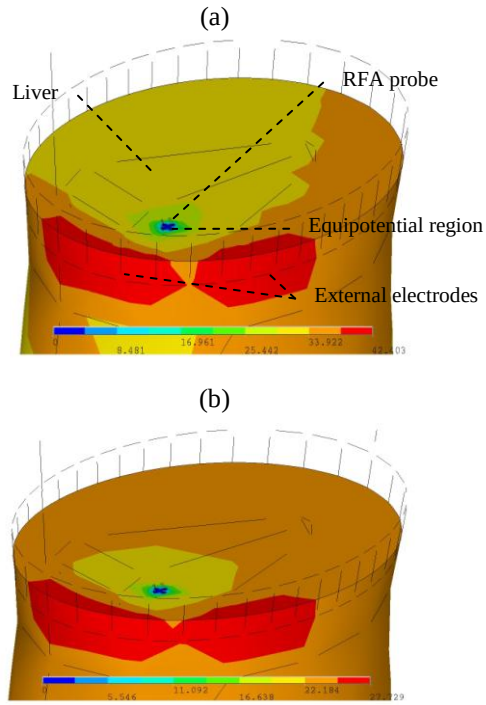

Fig. 2. Real (a) and imaginary (b) voltage distribution for and equipotential internal probe

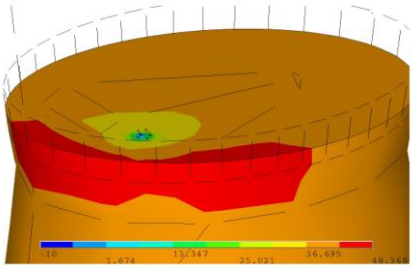

Fig. 3. Real voltage distribution for a non equipotential internal probe (the imaginary part is the same as in fig.2)

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