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Effects of saline volume on lesion formation during saline-infused radiofrequency ablation

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ABSTRACT

Radiofrequency ablation (RFA) is hindered when tissue temperature reaches 100 °C. At this temperature, tissue vaporization occurs, which prevents electrical currents from flowing into the tissue. Smaller lesions are created as a result. One way to overcome this is to infuse saline into the tissue prior to RFA. Saline can increase the electrical conductivity of the surrounding tissue due to the abundance of ions inside the solution. This permits a greater distribution of electrical currents that can lead to larger lesion sizes. Although this procedure has been shown to produce larger lesions, the technique is risky due to the potential for the saline to extravasate into healthy regions of the tissue; hence, leading to unnecessary ablation. A computational model is developed in this paper to predict the formation of lesion following saline-infused RFA. The model incorporates the transport of saline inside the tissue, the resistive heating during ablation and the formation of lesion through cell death modeling. Results show that there is an optimal infusion volume that leads to the largest increase in the lesion size. With further developments, the model may be used for the planning of saline-infused RFA treatment.

1. Introduction

Currently, there exist numerous methods for the treatment and elimination of hepatic tumors. These include methods such as chemotherapy (which utilizes chemicals that destroy rapidly multiplying cells) and surgery for larger tumors. Within this context, the usage of radiofrequency ablation (RFA) has grown in preference due to its minimal invasiveness and minor side effects compared to the other methods as described above. The procedure in a conventional RFA treatment involves the insertion of an ablation probe or needle into an area of tumorous cells. Electrical currents in the frequency range of 450 to 500 kHz is conducted along the probe and flow into the tissue, where the electrical energy is converted into heat via resistive heating. The rise in the tumor temperature induces necrosis, which causes the tissues to die. This is commonly referred to as cell death.

RFA is hindered when tissue temperature rises above 100 °C, resulting in the excessive formation of water vapor that surrounds the vicinity of the probe. The water vapor increases the overall electrical impedance, thus preventing electrical currents from flowing into the tissue. Smaller lesion sizes are formed as a result [1], leaving some of the tumorous tissues unablated. Various techniques to overcome this limitation have been proposed. These include the multiple application of RF at various sites of the tumor [2], the use of multi-tined RF probes [3,4], the use of internally-cooled RF probes [5,6] and the

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infusion of saline into the tissue prior to RFA [7]. All of these approaches have the same objective, that is, to increase the size of the lesion size. The present study focuses on the infusion of saline into the tissue prior to RFA. Saline, when infused into the tumor, can increase the electrical conductivity of the surrounding tissue due to the abundance of ions inside the solution. This permits a greater distribution of electrical currents that can lead to the formation of larger lesions.

Presently, tumors larger than 4–4.5 cm in diameter cannot be treated using the conventional RFA procedure mainly because the heat does not distribute over a large area. Furthermore, various other complications such as the excessive scarring of tissue or the creation of irregular lesion sizes mean that the treatment is not preferred in these conditions [8,9]. Saline-infused RFA therefore, appears to be a promising approach, not only to overcome the high impedance encountered during tissue vaporization, but also to enable larger tumors to be ablated. Nevertheless, given that often it is difficult to predict and to ascertain the motion of saline inside the tissue, there is a risk of extravasation or the leakages of saline into healthy regions of the tissue if excessive infusion is carried out. This will cause some part of the healthy tissue to be ablated, leading to undesirable damage. This in fact, has been confirmed in perhaps the only clinical trial on saline-infused RFA to have been reported in the literature [8]. At the same time, a perfusion rate that is lower than the required amount would not be sufficient to ablate the entire tumorous tissue, thus requiring multiple operations to complete the procedure [8].

Numerous experimental studies of saline-infused RFA have been carried out in the past for the purpose of understanding how the geometry and the lesion size are affected [7,10–12]. Most of these experimental investigations have been limited to ex vivo studies carried out using animal tissue samples. Overall, there is an increase in the lesion size when saline infusion is carried out prior to administering RFA [7,10,13,14]. A number of computational models that simulated the treatment of RFA have also been developed [15–17]. However, these models were largely used to investigate the correlation between the temperature distribution and the lesion size in a conventional RFA treatment without saline infusion. Models that included the effects of saline infusion are scarcely reported. Barauskas et al. [18] modeled the infiltration of saline into ex vivo liver tissue based on the proportion of saline that is present inside the liver. However, their model contains the unknown tissue saturation coefficient that has to be fitted to experimental data in order to obtain the value. Antunes et al. [19] adopted a more straightforward approach for modeling the effects of saline infusion. They divided the tissue domain into piecewise-homogeneous regions, where one of the domains is assumed to be completely saturated with saline, while the other domains have zero saline infiltration. In the domain saturated with saline, the electrical conductivity is prescribed by multiplying the baseline value with a factor greater than one.

Motivated by the lack of development of computational models and an incomplete understanding of the influence of saline during RFA, the present study seeks to bridge this gap by developing a mathematical and computational framework for simulating the treatment of saline-infused RFA. The framework will be used specifically to investigate the effects of saline volume on the lesion formation; information that has not been properly quantified in the literature. The investigations are carried out computationally using the commercial software COMSOL Multiphysics ®. A linear model is used to relate the tissue electrical conductivity with the local saline concentration. Flow of saline inside the interstitial space of the tissue is modeled by coupling the Darcy equation and the convection-diffusion equation [20]. The flow of electrical current and the subsequent heating of the tissue are described using the Joule heating model, which couples the electrical potential equation with the bioheat equation [21]. To quantify the size of the lesion formed, the recently developed three-state cell death model is used [22].

This paper is organized into six sections. In Section 2, the methodology employed in developing the computational model is outlined. The material properties and the assumptions underlying the model is outlined in Section 3. This is followed by results in Section 4 and discussions in Section 5. Section 6 presents the conclusions of the present paper.

2. Methodology

2.1. The model

A needle-like RF probe of radius 1 mm is considered in this study. The probe has an active part made of nickel-titanium with a length of 2 cm. The conductive part is connected to a stainless steel shaft, where its surfaces are electrically insulated. The tissue surrounding the probe is assumed to be liver. The choice of liver instead of tumor was made based on the consideration that most of the experimental studies in the literature were carried out on livers and not on tumors. A model based on the liver would permit a more direct comparison with these existing studies. The liver tissue is assumed to be homogeneous and isotropic and is spherical with a radius of 6 cm. The probe consists of four rectangular infusion holes, each with a cross-sectional area of approximately 1.75 mm^2. These infusion holes are placed at the four quadrants around the active part of the probe, such as shown in Fig. 1. To reduce the requirement for computer memory, the problem is assumed to exhibit symmetrical features in both the geometry and the physics, so that only one-eighth of the model needs to be developed. The developed model is illustrated in Fig. 1.

2.2. Governing equations

The entire process of lesion formation during saline-infused RFA can be modeled using three different models that describe the physical processes involved. The transport models consist of the flow and solute transport equations that are