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RESEARCH ARTICLE

On the cooling effect of flowing blood on hepatic tumor ablation process

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ABSTRACT

One method of removing malignant tissues from human organs is radiofrequency ablation. Thermal radiofrequency is a common technique of liver tumour therapy, which depends mainly on heating the infected region. This work proposes to investigate the thermal issue, which – in instance of excessive current – leads to extra lesion in liver tissues. However, the thermal lesions and the mistakes occurred in positioning the trocar instrument in the correct and accurate place arise the need to simulate and prediction of the thermal and electrical behaviour of the ablation operation. By using COMSOL multiphysics package, the process of hepatic tumour ablation has been simulated. Results show that by virtue of higher blood electrical conductivity, the nearby liver tissue around the electrode can be heated by rising its temperature due to electrical current from the radiofrequency probe according to the Joule law. Also, in this paper, different values of blood perfusion rate have been applied in the simulation process to investigate its effect on the ablation process. It is found that the increasing of mass flow rate of blood flow tends to bring down the fraction of necrotic tissue, which is contraindicated to the tumour ablation process.

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Simulation; cooling effect; hepatic tumour; radiofrequency; ablation

1. Introduction

According to the medical statistics, over one million people around the world are suffering from hepatocellular carcinoma [1–3]. Surgical option for therapy hepatic carcinoma is not always suitable one because of many restrictions like tumour size, location of the tumour or other clinical conflictions [4–6]. However, there is another option of treatment, which is radiofrequency RF ablation. RF method can destroy the cancerous tumours and eliminate it from normal tissue by heating the tissue to a severe temperature that kills the cancer cells [7,8]. The merits of radiofrequency thermal ablation show a good and reliable tool for the therapy of different types of hepatic tumours. Researchers try to simulate this process by using a set of mathematical equations, which can describe and predict the whole process [9–13].

Clasen et al. [14] performed trial contemplate in *ex-vivo* ox-like liver with mathematic demonstrating. They performed multiplier radiofrequency removal with inside cooled anodes. The outcomes demonstrate that the coagulation volume, short-pivot width and removal time were controlled by the power applied and the span of the tool.

Berjano [15] "played out an examination audit. He explored the best in class in hypothetical demonstrating as done in the overview of RF removal procedure. He inspected the vital components associated with this strategy, including the test approval and its limitations. In increase, his survey executed the portrayal without bounds extent of RF removal process".

Huang [16] "examined the impact of the vein on the warm injury development amid radiofrequency removal for liver tumours. In his investigation, results demonstrate the warm sore size abatements as the sore blood perfusion rate increments".

Dodd et al. [17] "carried a PC investigation of different values of tumours removal circle with different diameters and chose the optimum removal gadget".

Voglreiter et al. [18] "performed complete recreation investigation of radiofrequency removal treatment of liver tumours. By joining countless execution picture preparing, biomechanical reproduction and representation systems into a summed up specialised work process. Furthermore, they utilised the list of capabilities into a solitary, coordinated application

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(RFA Guardian), which misuses every single accessible asset of standard shopper equipment, including greatly parallel figuring on illustrations handling units. This allows to anticipate or imitate treatment results on a solitary PC with high computational execution and high precision. The subsequent low interest for foundation empowers simple and cost-effective joining into the clinical schedule".

The test ought to be embedded into liver tissue symmetrically generally a wrong and mistaken positions prompts some clinical difficulties. de Jong et al. [19] "examined the impact of Needle redirection in warm removal methodology of liver tumours in different scenarios. They found that needle avoidance was in excess of one millimetre, though 7% of the needles demonstrated a vast needle avoidance of in excess of three millimeters".

Up to publishing date of this study, weak attention is directed to investigation of the cooling effect of flowing blood and simulation of hepatic tumour ablation process by using software package COMSOL multiphysics by other researchers. In this study, the attention is focussed to investigate the influence of cooling effect of flowing blood in veins and arteries in the adjacent tissue next to RF instrument and how this affect the ablation process which mainly depends on heating the infected region to kill the cancerous cells.

2. Mathematical model

2.1. Blood flow

The well-known Naiver–Stock equations are used to simulate the flow of blood in order to get better understand to the role of blood vessel nearby tumour region in cooling process. The blood is assumed to be homogeneous, incompressible, Newtonian fluid and has an average uniform density. The flow is assumed to be uniform, laminar, two-dimensional, steady-state with no-slip conditions. The set of differential equation describe the flow are written below for continuity, momentum and energy equations [20]:

$$\frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} = 0 \quad (1)$$

$$\frac{\partial(\rho u u)}{\partial x} + \frac{\partial(\rho v u)}{\partial y} = -\frac{\partial p}{\partial x} + \frac{\partial}{\partial x}\left(\mu\frac{\partial u}{\partial x}\right) + \frac{\partial}{\partial y}\left(\mu\frac{\partial u}{\partial y}\right) \quad (2)$$

$$\frac{\partial(\rho u v)}{\partial x} + \frac{\partial(\rho v v)}{\partial y} = -\frac{\partial p}{\partial y} + \frac{\partial}{\partial x}\left(\mu\frac{\partial v}{\partial x}\right) + \frac{\partial}{\partial y}\left(\mu\frac{\partial v}{\partial y}\right) \quad (3)$$

For the Newtonian fluid, the viscous stresses resulted by the virtue of blood flow in arteries and veins are related linearly to the strain which is the gradient of velocity per the gradient of displacement and this represents the rate of change of blood vascular deformation over time.

2.2. Heat transfer

The heat transfer process in biological tissue can be expressed as [12]:

$$\delta_{ts}\rho C\frac{\partial T}{\partial t} + \nabla.(-k\nabla T) = \rho_b C_b \omega_b (T_b - T) + Q_{met} + Q_{ext} \quad (4)$$

Heat transfer also occurs in various sections of the probe. It is evident that for these parts which, is metallic the right hand side is zero and the temperature is assumed to be initially 37 °C.

In addition to the heat transfer equation, this model provides a calculation of the tissue damage integral. This gives an idea about the degree of tissue injury α during the process, based on the Arrhenius equation:

$$\frac{d\alpha}{dt} = Ae^{\left(-\frac{dE}{RT}\right)} \quad (5)$$

where A is the frequency factor (s^{-1}) and dE is the activation energy for irreversible damage reaction (J/mol). These two parameters are dependent on the type of tissue. The fraction of necrotic tissue, θ_d, is then expressed by:

$$\theta_d = 1 - e^{-\alpha} \quad (6)$$

2.3. Electric current

The main idea of supplying electric current in the tumour area is to convert the electrical energy into thermal energy according to the law of conservation of energy. The governing equation of the Electric Currents interface can be described mathematically as

$$-\nabla(\sigma\nabla V - \boldsymbol{J}^e) = Q_j \quad (7)$$

where $\boldsymbol{J}^e$ an externally generated current density (A/m^2), Q_j the current source (A/m^3). In this model both $\boldsymbol{J}^e$ and Q_j are zero, substituting these values and simplify to get:

$$-\nabla(\sigma\nabla V) = 0 \quad (8)$$

The value of supplied voltage initially set to be 22 V while at the cylinder's outer boundaries is set to zero

Boundary condition	Value
Electric current	*zero voltage at cylinder wall* *intial voltage on the electrode surfaces*
Heat transfer equation	*temperature is equal to blood temperature on blood vessel wall* *on the interior boundaries temperature is determined by mathematical model*

volt potential. The boundary conditions adopted in this study are as follows:

Using these boundary conditions and substituting their values in the model equations, it is possible to get the temperature distribution throughout the tissue as a function of time and the percentage fraction of necrotic tissue that subjected to electrical field.

3. Simulation process

In order to simulate this bio-medical case, let us understand how this process is done medically. The physical principle of the process depends on the heating the required region of tissue above 45 °C and above. To achieve that a local heat source is needed which is the small electric probe. The probe is consisted of two parts: the first is the major rod (called trocar) which is well insulated electrically except near its arms and the second is four electrode arms as shown in Figure 1. By supplying the electric power, an electric field will flow in the tissue and heat it causing a remarkable increasing in its temperature. The temperature distribution throughout the tissue is not uniform, nearby regions have highest temperature since it is exposed to strongest electric field.

In this paper, three models are implemented in simulation process, biological heat transfer model, electric current model, a multiphysics characteristics and electromagnetic generated heat. The basic approach is to model the body tissue with a large cylinder. The temperature remains at 37 °C during the entire procedure. One of the basic issues in the ablation process is the orientation of the probe which must be inserted orthogonally in the tumour. Therefore, the tumour is assumed to be located in the middle centre of the cylinder while its physical properties is assumed to be as the same as these of normal surrounding tissue. The time of whole process is considered to be ten minutes which is usually adopted in similar medical operation to remove the whole malignant tissue completely.

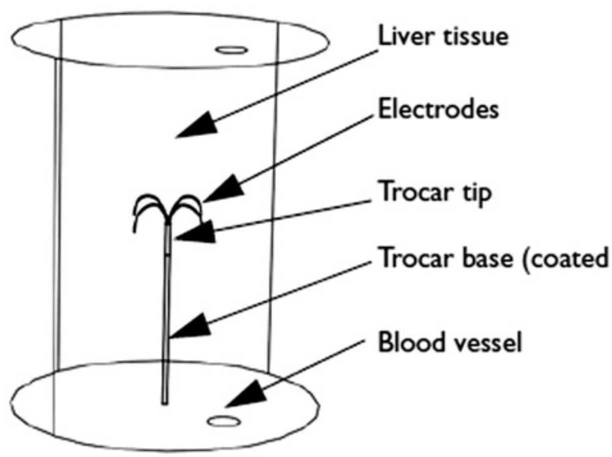

Figure 1. Cylindrical modelling domain with the four-armed electric probe in the middle, which is located next to a large blood vessel [12].

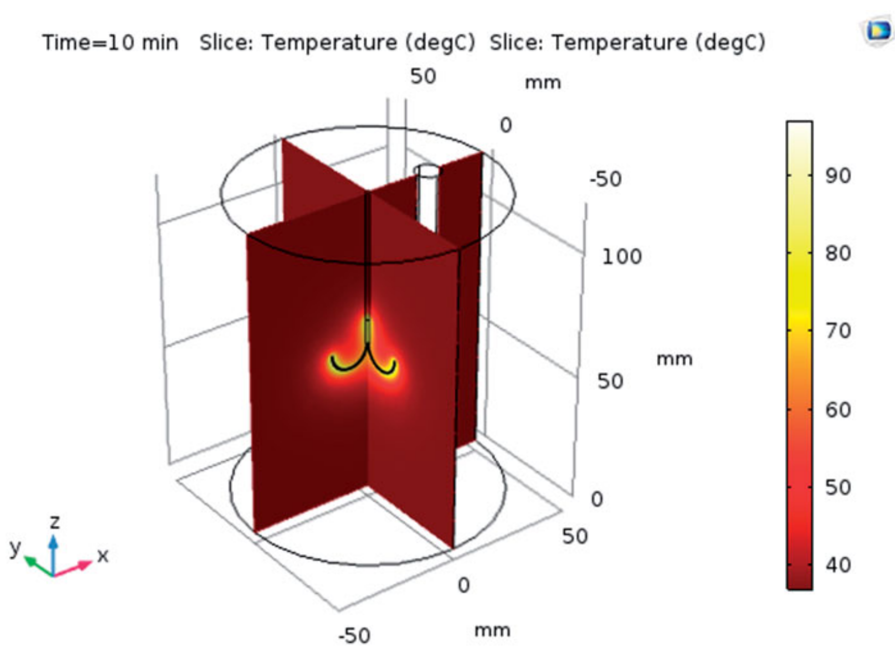

Figure 2. Temperature contours illustrating temperature distribution in the region.

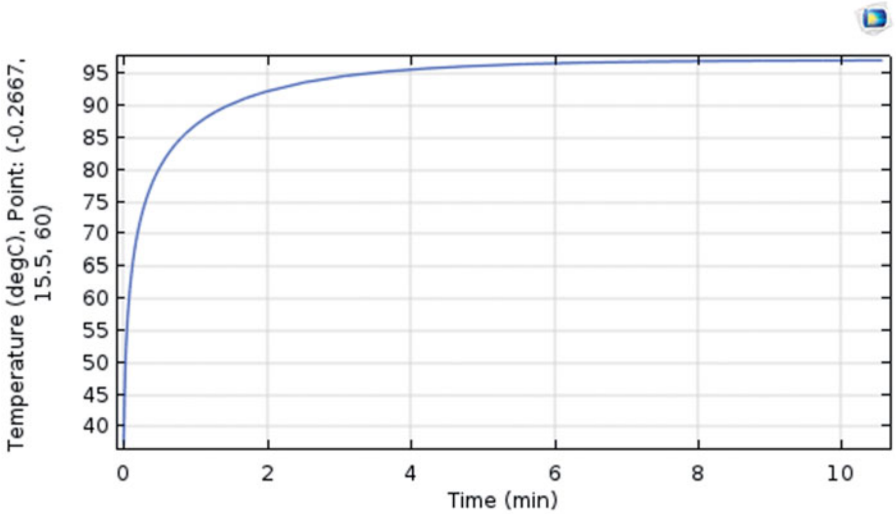

Figure 3. The Temperature rise over time at the tip of one of the electrode arms.

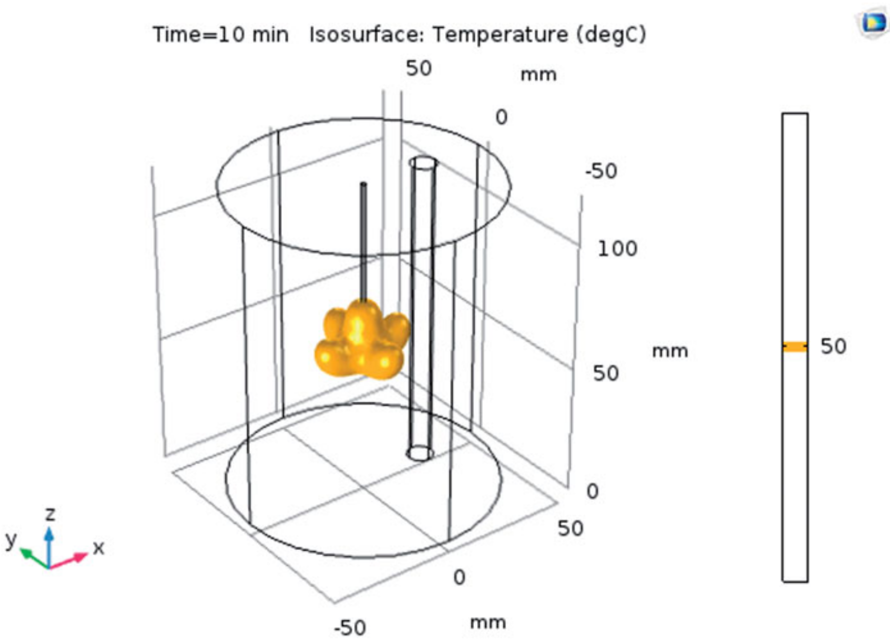

Figure 4. Visualization of thermal lesion formation at time $t = 10$ min.

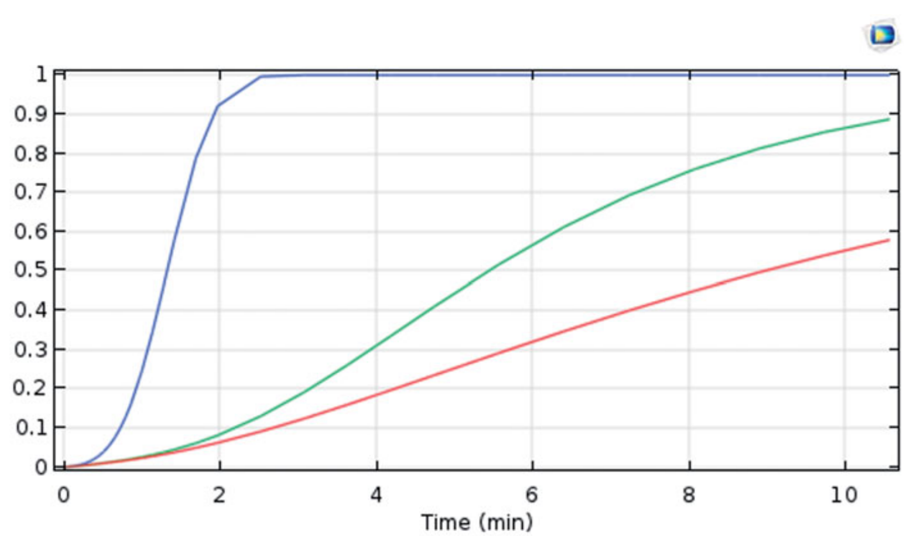

Figure 5. Fraction of necrotic tissue at three points above the electrode arm.

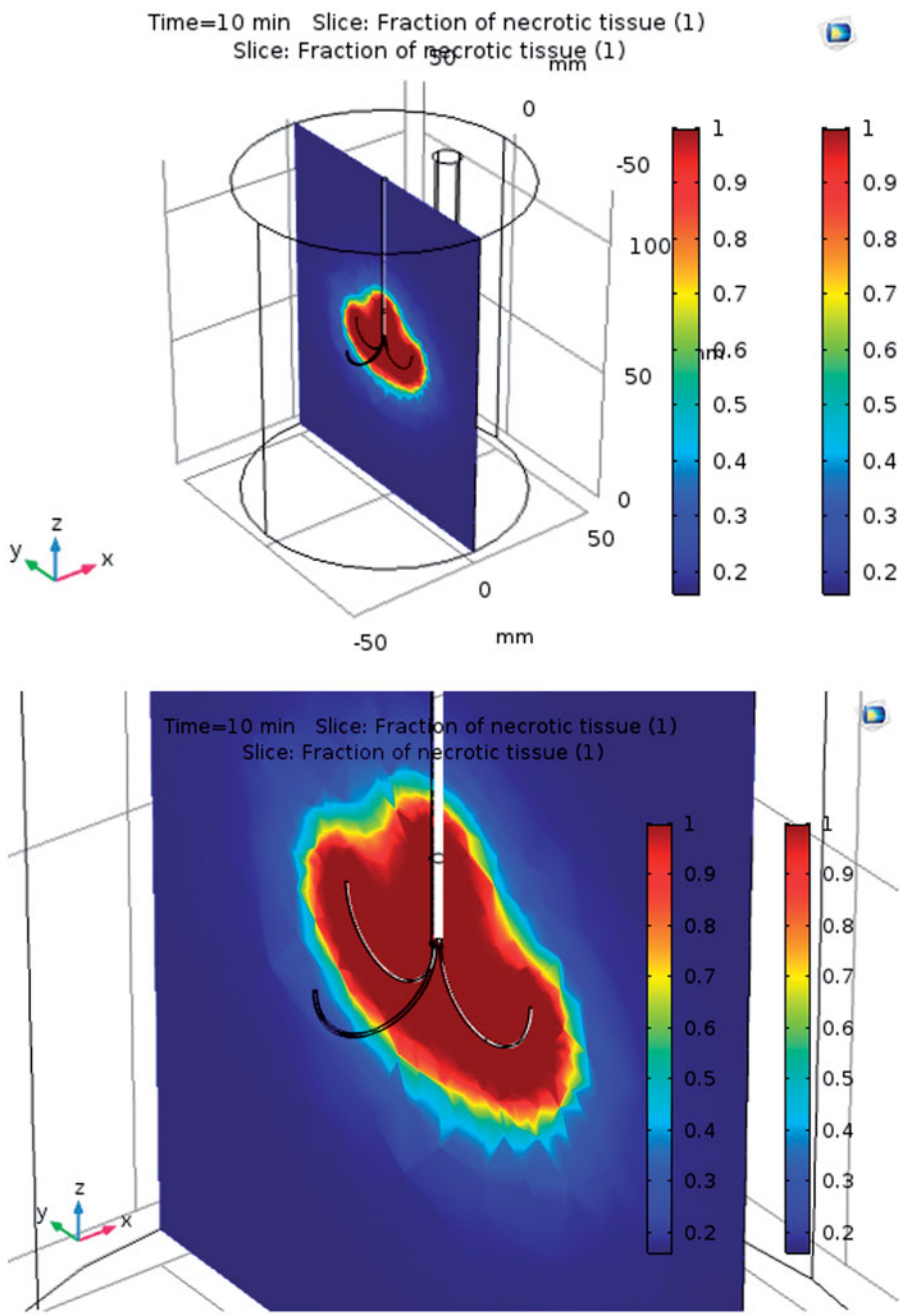

Figure 6. Fraction of necrotic tissues.

4. Results and discussion

Thermoelectric phenomena have been considered, and the coupling between them has been described. By applying the boundary and initial conditions in the governing equations, results show how the heat propagates throughout the objective tissue and how temperature contours were distributed. In addition, the result from the simulation process also visualises the parts where the cancer cells are died. Figure 2 shows the temperature distribution in the liver tissue at the end of the ablation process which is meant the tenth minute. Results indicate that the tissue next to probes is heated up to 90 °C. This is occurred because of heat accumulation throughout the process, which rise the temperature over and over till the end of operation as shown in Figure 3.

When temperature reaches 50 °C and above, the malignant tissues and cancer cell begun to destroy because of the heating effect. Figure 4 shows the shape of thermal lesion after destruction of cancer cells. The resulting shape like mushroom shape since the instrument when opened it looks like an umbrella.

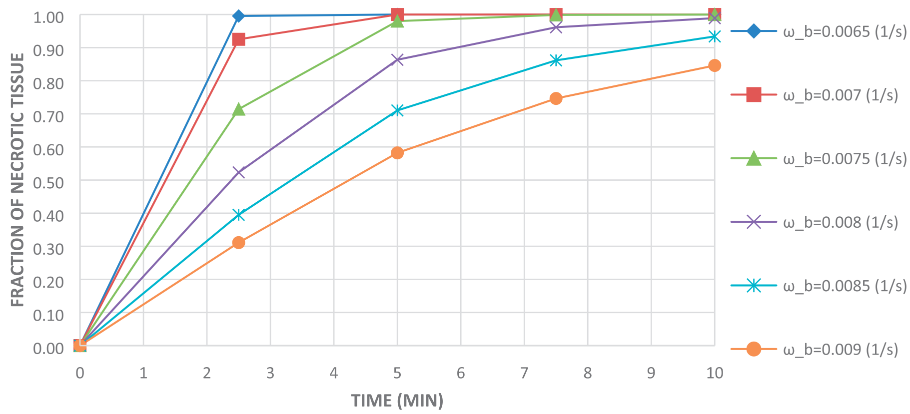

Figure 7. The relationship between process time and fraction of necrotic tissue at different values of blood perfusion rate.

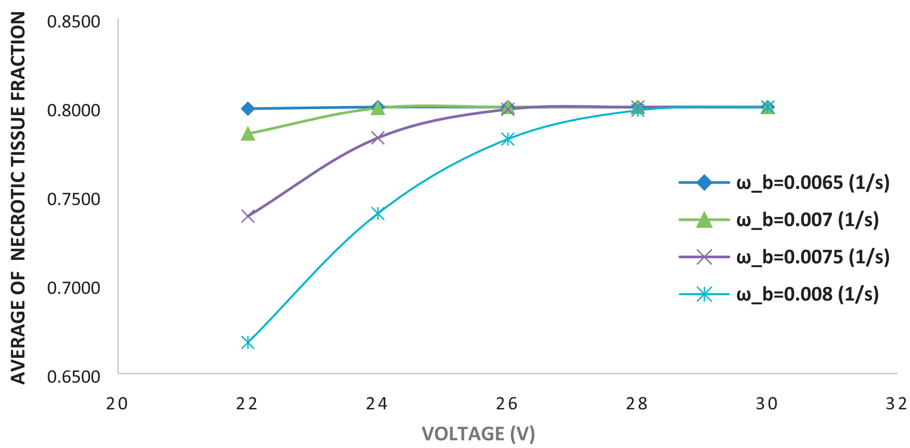

Figure 8. The average of fraction of necrotic tissue versus supplied voltage at different values of blood perfusion rate.

The most important results from simulation are the fraction of necrotic tissue, which represents how the cells are affected by temperature rise at each point. The nearby region, which is located in the upper portion of trocar tip, is exposed to heat generated in probe more than the others. Therefore, it has higher portion of necrotic tissue through the time of process and after two minutes it reaches the steady-state process as indicated in Figure 5. According to the Joule effect, the higher is the supplied voltage the higher is destroyed cells. Figure 6 represents the zones of destroyed cells where the red zone represents the completely destroyed cells while in the other zones gradually decreased. If we rise the value of supplied electrical power then the red zone will be much higher.

Two parameters here are playing a important role:

- To overcome the cooling effect of flowing blood in blood vessel, an increment in the supplied voltage to enhance the electrical power and hence the heat generated.
- To guarantee full destruction of malignant tissue, electrical power supply may be increased but not it should not exceed its effect over adjacent normal tissue.

For the first factor, the blood flow depends mainly on perfusion rate which is the process of a body delivering blood to a capillary bed in its biological tissue. Thus, the higher is the perfusion rate, the higher is the cooling effect of blood and in such a way lowering the heating effect, which is required to kill the cancer cells. In this study, a different value of blood rate perfusion applied in the software package and results obtained. Figure 7 shows the effect of increasing the blood perfusion rate of blood in the near veins and arteries. Consequently, the ablation process may not be able to completely destroy the tumour and the number of killed cells is decreased. This effect is consider negative effect for the process of ablation. In order to overcome the cooling effect on ablation process, the supplied voltage should be increased till the fraction of necrotic tissue become unity. Sometimes – especially in clinical complications like hypertension – even increasing the supplied voltage does not lead to full destruction of malignant tissue during specific period of operation time as shown in Figure 8.

The diameter of the major vein and the blood velocity are implicitly indicated in the equation of flow rate of flowing blood in it. Since according to the general equation of flowrate of incompressible fluid which states that the flowrate is equal to cross sectional area time velocity and this is also reflected in the value of blood perfusion rate which equal flowrate per unit volume. Figures 7 and 8 are displaying different values of blood perfusion rate.

The adjacent layers next to the tumour can be modelled as multi-layer thermal resistance. Thus, according to Fourier's law $Q = -kA(dT/dx)$ or $\nabla^2 T = 0$ in three dimensional and steady state, the quantity of heat transfer is inversely proportional to the distance from the tumour to the major vein which is represented by (dx).

5. Conclusions

Thermally significant blood vessel could damage RFA lesion formation. Reduced blood flow rate is recommended to remove (or reduce) heat sink or cold spot in the lesion formation. Particularly, convection heat transfer dominates in a short distance range. The lesion which is formed by heat exposure is observed according to the intensity of electric current. The heat that is generated in the instruments can also dissipated by cooling effect of flowing blood in the various hepatic veins and arteries.

The operation time should be set to an optimum value in order to avoid extra-exposure of liver tissue to heat field, taking into account the value of blood perfusion rate. Optimized value of the supplied power should be also taken into account to perform good and perfect ablation process at reasonable time period.

Disclosure statement

No potential conflict of interest was reported by the authors.

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