Theoretical Analysis of the Extended Effect of Radiofrequency Thermal Ablation Process: A Case Study of Liver

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ABSTRACT
The success of the radiofrequency ablation (RFA) in treating liver has shown great success. Recently, greater successes are achieved however without its challenges. Possible side effects after ablation therapy include abdominal pain, infection in the liver, and bleeding into the chest cavity or abdomen. The mathematical expression for the conversion of sound to heat energy was used to investigate the conductive transference of heat energy from the ablation zone to the surrounding tissues. We considered two groups of probes and the maximum energy available for transfer. It was discovered that probing technique is capable of releasing heat energy of 120 J for each probe from each ablation zone. This omission is very critical for clinical processes. For above ten ablation zones, enormous transference of energy to the neighbouring tissues is further enhanced by the differential tissue impedance. Hence, there is more danger when excess tissue impedance is imposed on the ablation zones.

1. INTRODUCTION

Radiofrequency ablation (RFA) is one of the recent techniques used to treat benign, cardiology treatment, i.e., treatment of heart disorders, gastro-esophageal reflux disease, cornea surgery, malignant liver, lungs, prostate, breast and bone tumours. RFA has more advantages over other ablation techniques (1) (e.g. rapid patient recovery, less complication after treatment, faster to administer) its shortcoming is not only bleeding and the development of infections but thermal injury to tissue structures, such as lung injury or collapse during the procedure, damage of the gall bladder or bowel. This technique makes use of radiofrequency as thermal energy without the long incisions traditionally used in early tumour surgeries. The radiofrequency ablation device consists of energy producing electrode an Ablator, radiofrequency generator, and a control console. The electrode is found at the tip of the ablator and it consists of a metal shaft which is insulated. Through the electrode, the radiofrequency generator provides radiofrequency energy to the tissues. While the electrodes are placed in the ablation zones using the ultrasound, CT or magnetic resonance imaging, the radiofrequency

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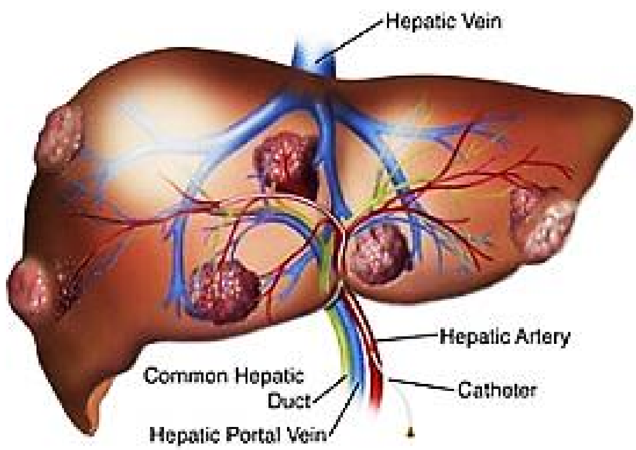
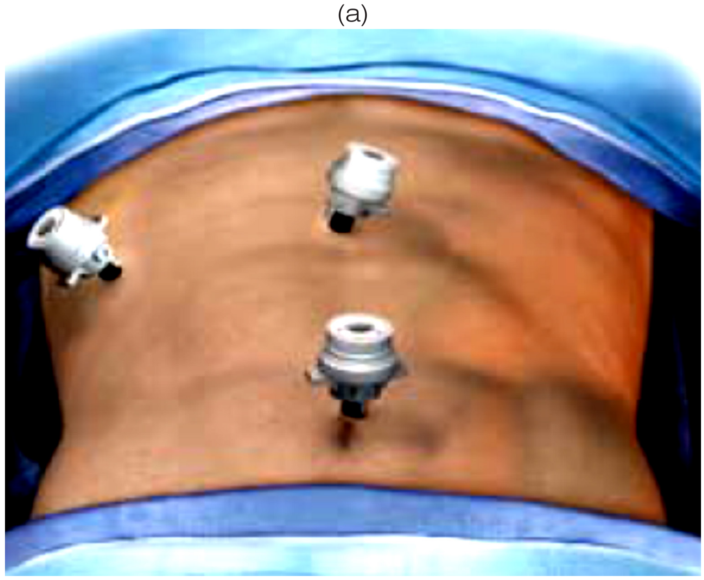
generator initiates RF voltage between the electrode and the grounding pad which generate lines of electric force fields. However, the potential of the physics of this arrangement cannot be underestimated because of the possibilities of expanding its operational algorithm. The wave natures of RFA heating processes have not been adequately explored. For instance, is the diffusion of heat as soon as the energy is released (2) or grows gradually with thermal relaxation time (3)? Consider a theoretical tumour (of high blood perfusion from large vessels to hepatic artery and vein network throughout the organ) shown in figure 1a below. How can the RFA therapy be safer for the patients without heat sink effects (2)? What is the success rate of this operation?



(a)



(b)

Figure 1a: A theoretical liver tumor (http://www.knowabouthealth.com);
Figure 1b: Probing technique during RFA operation on the liver

Experimentally, it is acknowledged that large vessel blood flow and microvascular perfusion affects the results of RFA (3). The physics of this known fact can be ascribed as the effect of changing geometries. The effect of changing geometries extends the physics of flow effects, RFA limitations etc. For example, it has been experimentally and theoretically proven that the heat sink effect and the vascular flow are connected (4,5). Hence, if the lethal cell temperature for tumours is 50 °C (6), more power is required to cool the electrode. Therefore, the task required to eliminate tumours shown in Fig. 1a may be a herculean task to prevent damage of other tissues of the affected organ.

In this paper, we examined the mathematical implication of the most successful techniques used for the RFA therapy of the liver and the extent of its challenge which mitigates its success. In section two, we considered the theoretical background of the science of the RFA generators and needles. In section three, the theoretical formulation of the conductive heat transfer within the intra or intercellular ablation zones were considered with its experimental implications. In section four, the application of the model in a dummy experimentation was performed.

2. THEORETICAL BACKGROUNDS

Many theories have been propounded to drive the RFA, however few questions on its validity must be answered to foster a unified understanding of the RFA and how it can be improved upon. The size of the RF current density is simplified by the ohms law shown below

$$J = -\sigma \nabla V = \sigma E \tag{1}$$

Where E is the electric field, V is the potential and σ is the electrical conductivity. From theory, electrical conductivity depends on temperature of the tissue, ion concentration in the tissue and frequency of the applied electric field which has been regulated to an RF range of 300kHz – 1MHz. From the above equation, various heat equations emerged. For example, the modified unsteady heat equation (3) is given as

$$\frac{\partial^2 T}{\partial t^2}(x,t) + \frac{1}{\tau}\frac{\partial T}{\partial t}(x,t) - \frac{k}{\rho c \tau}\Delta T(x,t) = \frac{1}{\rho c \tau} Q(x,t) + \frac{1}{\rho c}\frac{\partial Q}{\partial t} \tag{2}$$

Where T is the temperature, t is the distance, x is the displacement of flux, ρ is the density (kg/m3),τ is the thermal relaxation time, Q is the joule heating and c is the specific heat (J/kg K). However, the thermal relaxation time variation (3) in the hyperbolic bioheat equation and Pennes bioheat equation exposes the inadequacies of the theory of the RFA. In reality, RF ablation environment are affected by blood perfusion i.e. the blood convection cooling effect plays an important role at the electrode tip where the maximum temperature of the RFA device should exist. Therefore, the mathematical representation of the blood perfusion effect is given (7) as

$$Q_p = \beta \rho_b c_b \omega_b (T_b - T) \tag{3}$$

Here ρ_b is density of blood, c_b specific heat of blood, T_b blood temperature, ω_b blood perfusion coefficient and β is blood perfusion coefficient (ranges from 0 and 1). Hence, the thermal technique requires the consideration of abnormal conductive tissue in two major categories i.e. heat-based and cold-based procedures. This is also dependent on the electrical properties of the tissue. The electrical property of the abnormal conductive tissue depends on its composition and structure. The extensive effect of the abnormal conductive tissue is the determination of the joule heating and temperature distribution.

3 THEORY FORMULATION

The basic requirement of the RF range is given as 300 kHz – 1 MHz. The electric field applied through the electrode to a tissue can be described by RF source given by Ref [7-9]

$$\frac{\hbar^2}{2m} {E_r}^2 \frac{\partial}{\partial t}(\mathrm{B_r} - eA) = \beta B_r f_r e^{-j\beta r}(sin\theta + cos\theta) \quad (4)$$

Here j is the radio frequency current, m represents the magnitude of the electrons, f_r is the spin factor which determines the electron spin along the horizontal component within the magnetic field, r is the radius of each ablation zones, β is the frequency of cooling power. The bio-heat transfer (BHT) can be estimated via the total convective transfer between tissue and blood. BHT is dependent on vessel size, changing vessel geometries in surrounding tumour area, blood flow velocities and number of vessels in the volume of interest. However, the known methods for solving the variables listed in the later are the effective conductivity and Pennes bio heat equation. While the Pennes bio heat equation considers heat exchange between blood and tissue which occurs in the capillary bed, the effective conductivity equation considers the heat exchange between fluids. Hence, the structures of biological tissues in relation to the incident wavelength or frequency are important factors that determine the relative amount and pattern of RF energy. Hence via equation 4, we shall be deriving the governing equations that express the physics of bio-heat equations. If we consider the impact of RF energy on tissue effect in form of wave form, the solution of the standing waves in the tissue (see figure 1) is given as

$$E_r = 1, \quad B_r = \beta r, \ \mathrm{a}=1, \quad A = 0, \quad \emptyset = \emptyset(r,\theta), \ f_r = 1, \hbar^2 \approx 2m \ \ \beta \in \mathbb{R}$$

Hence, the equation describing the heat flow waveform can be written as

$$\frac{\partial r}{\partial t} + kre^{-j\beta r} = 0 \quad (5)$$

Here $k = \beta(sin\theta + cos\theta)$

If we consider the current density flow from the electrodes, the solution of the maximum heat conveyed from the electrode is given as

$$B_r = 1, \ \mathrm{a}=1, \quad A = 0, \quad \emptyset = \emptyset(r, \theta = 0), \ f_r = 1, \hbar^2 \approx 2m \ \ \beta \in \mathbb{R}$$

Hence, the equation describing the heat flow waveform can be written as

$$j = \frac{1}{\beta r} \ln\left(\frac{E_r}{\beta}\right) \quad (6)$$

In the practical sense of equation in live experiments the heat flow waveform is experienced as

$$j = \left(\frac{1}{\beta r}\ln\left(\frac{E_r}{\beta}\right)\right)_1 + \left(\frac{1}{\beta r}\ln\left(\frac{E_r \sin(\theta)}{\beta}\right)\right)_2 + \left(\frac{1}{\beta r}\ln\left(\frac{E_r \sin(2\theta)}{\beta}\right)\right)_3 + \left(\frac{1}{\beta r}\ln\left(\frac{E_r \sin(3\theta)}{\beta}\right)\right)_4 \ldots (7)$$

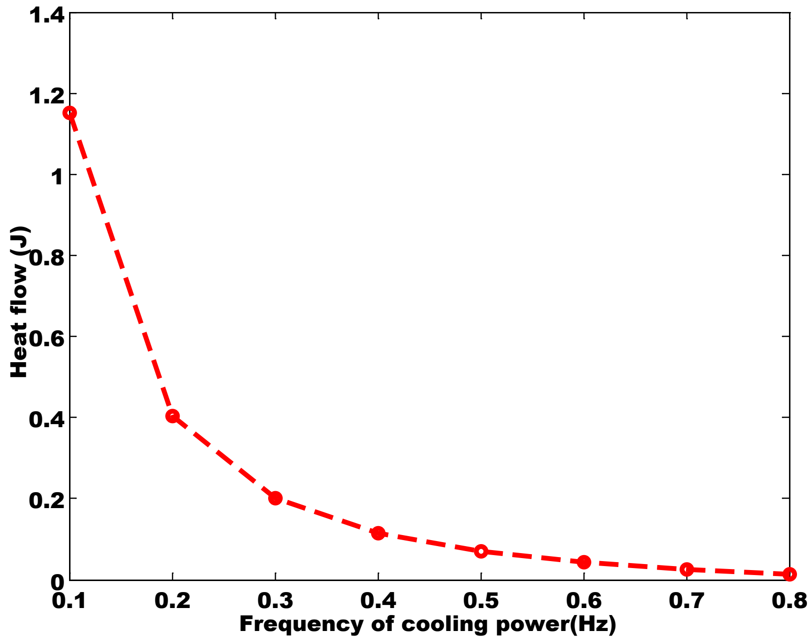
4. METHODOLOGY

The virtual experimentation that examines the heat flow waveform experienced in the body cell is shown in Figure 1a. The specification of the experimentation was discussed in the previous section. We considered two groups in the virtual experimentation, that is, Group 1 which is the mono-polar or single probe as shown in equation (6); and Group 2 which is the multi-probe bipolar as shown in equation (7). The MATLAB was used to show the effects expected on the surrounding tissues when any of the groups are considered. Hence, both groups mimic a live operation which is dependent on the number of ablation zones. However, in this study, we consider a single ablation zone and project its cumulative results on whatsoever number of ablation zones considered. Most scientists chose a minimum of ablation zones.

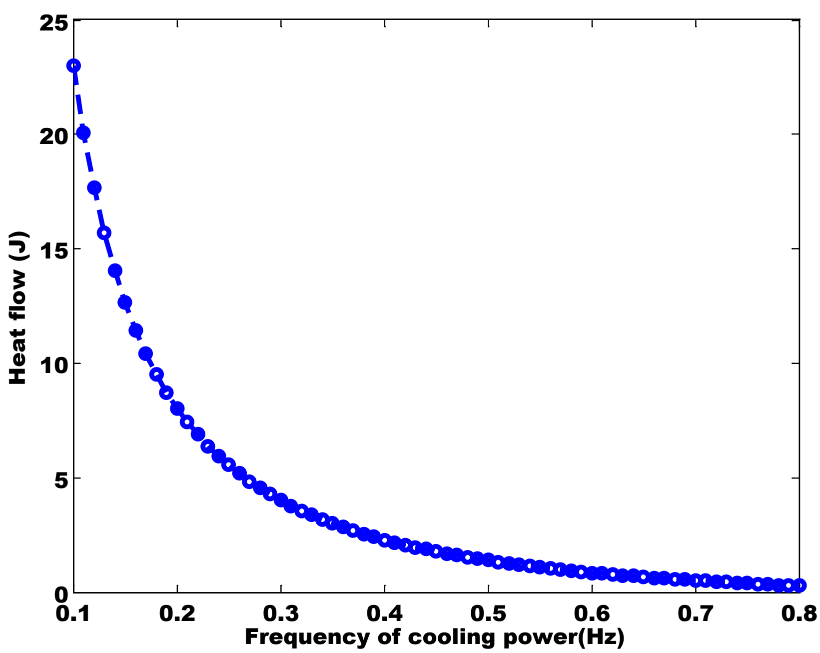
5. RESULTS AND DISCUSSION

The sampling of the 'r' term in equation (7) was intensified since the zone of coagulation necrosis correlate with the white central area of the RF induced ablation zone (10). Hence, we assume from Figure 1a that the 'r' term resolves the complexities in both the vertical and transverse diameter in a mono or bipolar probe (11,12). Some authors have suggested that the tissue impedance in the RFA probe should be within the ranges of 50Ω and 150Ω (11). Recall that tissue impedance contains both conducting and dielectric terms. Hence, the proteins and water-insoluble lipids around the liver i.e. gall bladder, bowels and lungs have the tendency of sympathizing with the liver when the tissue impedance is increased or decreased. This assumption is true because liver sometime determines the density of the lipoproteins around its vicinity when synthesizing Triacylglycerols (13). Secondly, the intracellular resistivity is typically 0.7 Ω m and extracellular resistivity is typically 1.1Ωm (14).

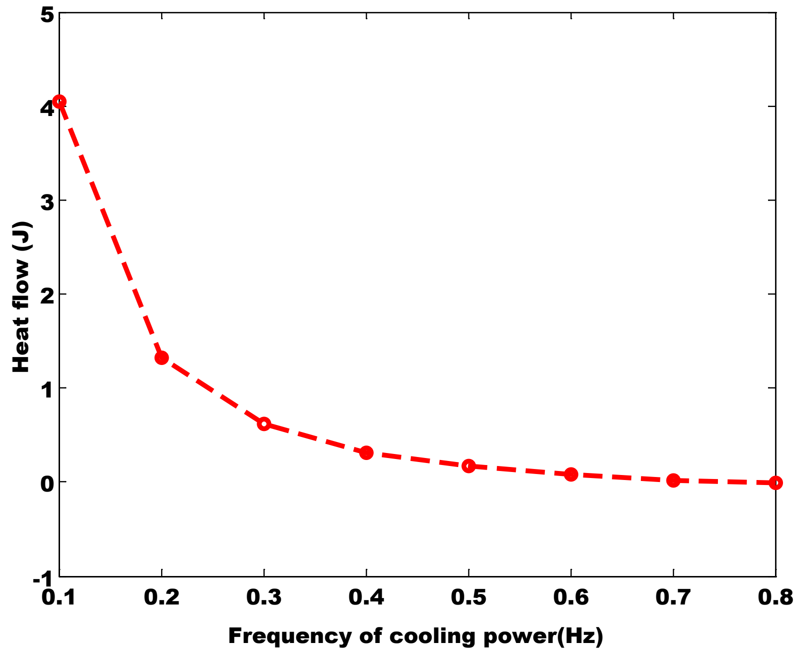
Therefore, we examined the expected energy transfer to the neighbouring tissues or organs during the RFA operation on the liver using a mono-polar or a single probe bipolar. We assumed a case where the diameter of the coagulation necrosis is 0.2 to 0.8 cm. If the electrodes are placed vertically above the ablation zones, it is expected to transfer energy of about 1.18J into the neighbouring tissues as shown in Figure 2a. This depends on the frequency of cooling power which is expected to decrease gradually beyond the ablation zone. Hence, it explains the mystery in the variation of the mean temperature at 15 mm from the electrode as illustrated by Lee et al. (11). The conductive energy transfer is highest for the bipolar probe which is expected to generate higher temperature. Hence, if the electrodes are inclined to the ablation zones, this heat flow has the tendency of reaching the other tissues faster since there is differential impedance between the ablation zones and the surrounding tissues. From Figure 1c, the energy transfer to other tissues may be as high as 4J. Under this condition, if a patient is placed on a series of RFA operations or above ten ablation zones, the probability of damage to the lungs, gall bladder or bowel is high. The danger may be more when tumour location is adjacent to the blood flow within the ablation zone. The attempt to generate sufficient temperatures to destroy the entire tumour triggers the conducting properties


1.4
1.2
1
0.8
0.6
0.4
0.2
0
Heat flow (J)
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
Frequency of cooling power(Hz)

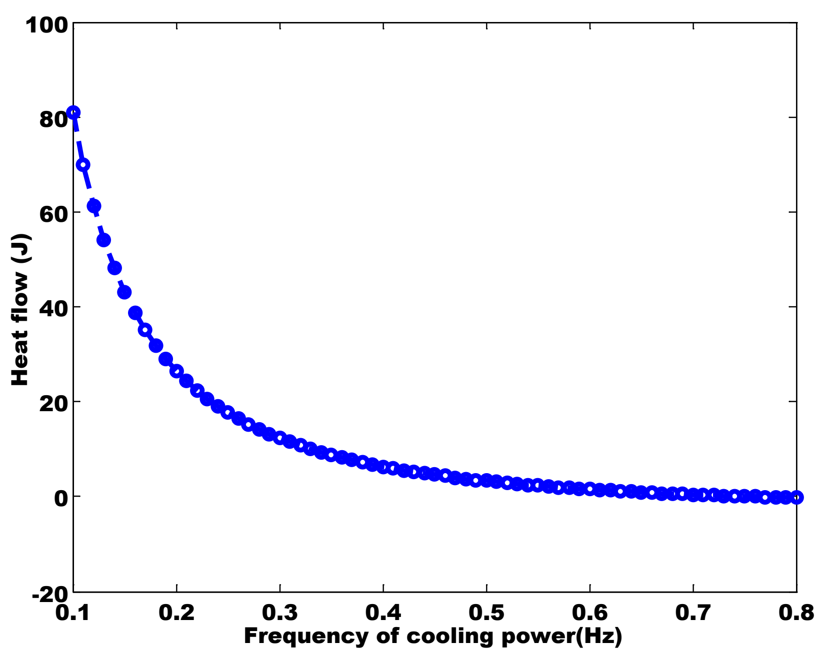
(a)


25
20
15
10
5
0
Heat flow (J)
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
Frequency of cooling power(Hz)

(b)



(c)



(d)

Figure 2 a-d: Heat transfer pattern from ablation zone to surrounding tissues of the differential low-density lipoproteins around the tissues close to the liver (15-17). The physics of this complexity is that the diameter of the coagulation necrosis might have extended to 2 to 28 cm.

Secondly, we examined the expected energy transfer to the neighbouring tissues or organs during the RFA operation on the liver using a multi probe bipolar. It was observed that the energy transfer was as high as 23 J (Figure 2b) when the diameter of the coagulation necrosis is 0.2 to 0.8 cm. Therefore, when ten ablation zones are considered, a minimum energy transfer to the neighbouring tissues would be about 230 J. However, in practical terms the cumulative energy transfer may be less or more than 230 J. if the electrodes are inclined to the ablation zones, the energy transfer could be as high as 80 J (Figure 2d). Hence, we expect a minimum of about 600 J if ten ablation zones are considered.

What is special about the inclined probe technique? From figures 3a & b, we can appreciate the geometrical importance of inclined probe technique and equation 6 & 7. It is observed that most medical practitioner use this method without abruptly.

6. CONCLUSION

The subtle conductive or convective heat transfer from the ablation site in the liver to the surrounding issue remains a problem that has undermine the great success of RFA therapy. The physics of the tissue impedance, geometrical application, operational algorithm, number of ablation zones e.t.c. cannot be ignored. It was shown that the surrounding tissues could receive above 600 J of transferred energy. The frequency of cooling power explains why any given temperature from any probe technique could amass great potential of affecting tissues far beyond the ablation zones. The issues of inclined probing were explained because heat flow has the tendency of reaching the other tissues faster since there is differential impedance between the ablation zones and the surrounding tissues.

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