International Journal of Thermal Sciences 80 (2014) 41–47

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

journal homepage: www.elsevier.com/locate/ijts

Parametric sensitivity analysis of radiofrequency ablation with efficient experimental design

E.Y.K. Ng*, Muhammad Jamil

School of Mechanical and Aerospace Engineering, College of Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798, Singapore

ARTICLE INFO

Article history:
Received 22 June 2013
Received in revised form
30 January 2014
Accepted 31 January 2014
Available online 4 March 2014

Keywords:
Pennes bioheat equation
Radiofrequency ablation
Taguchi orthogonal arrays
Control system design
Quasi-static approximation

ABSTRACT

The aim of this research is to analyze the efficacy of radiofrequency ablation (RFA) for varying electrothermal parameters. An attempt has been made to study the RFA for the effect of thermal conductivity, electrical conductivity and blood perfusion rate with Taguchi's design of experiments methodology. Their combined effect was analyzed quantitatively in different tissues. It was found that ablation volume for temperature control algorithm is mostly affected by blood perfusion followed by electrical conductivity and thermal conductivity. Smallest ablation volume was observed in kidney tissue while largest lesion volume was obtained in muscle tissue. Based on the results some insightful corollaries were drawn which may be translated as qualification of RFA for the respective tissue treatment protocol. Moreover, quantification of parameter sensitivity translates to efficient design of control algorithm for power delivery. It is intended that these conclusions will help the radiologist in the treatment planning stage and would serve as broad guidelines for the application of RFA in varying biological environment.

1. Introduction

Radiofrequency ablation (RFA) has been a relatively new form of therapy in the armamentarium of cancer treatment. It belongs to a group of therapies known as thermal therapies which rely on the tissue properties to generate the heating effect [1]. In these therapies the lethal effect of heat is harnessed and temperature of the tissue is raised above a threshold to cause lethal effects. Juxtaposedly, the lethal consequence of heat has a remedial effect for cancer and results in death of cancer cells. Mild temperatures (>42 °C) known as hyperthermic cause cell death by apoptosis [2]. Mostly these are used as an adjunct therapy to increase the effectiveness of other therapies like radiation therapy and chemotherapy [3,4]. Temperatures above 45 °C are known as thermoablative. Prolonged exposure at such high temperature destroys the cells via coagulation necrosis [5].

RFA has been used for treatment of cancer in various tissues like bone, fat, heart, liver, kidney, etc [6–12]. Goetz et al. used RFA to treat painful non-treatable metastatic tumours to relieve pain [6]. Bitsch et al. studied the effect of vascular perfusion on the lesion size in bovine livers [13]. Berjano et al. simulated RFA for atrial tissue using finite element model [10]. Yoon et al. reported that efficacy of RFA can be increased with renal artery occlusion for treatment of VX2 tumours [14]. Steinke et al. treated large tumours in lung metastases. They showed that large tumours are associated with high risk of recurrence owing to difficulty in achieving complete ablation [15].

Biological tissues vary in terms of electrical conductivity, thermal conductivity and blood perfusion as shown in Table 1. Bone and fat have lesser blood perfusion while kidney is the one with highest perfusion. Fat has lowest thermal conductivity while liver has the highest thermal conductivity of the tissues analyzed. Similarly, muscle tissue has the highest electrical conductivity and fat is the one with lowest electrical conductivity. This variation encountered in the properties of different tissues is bound to have varied repercussions for the output of the therapy.

The heating mechanism in RFA is mainly resistive. Applying potential difference between the active electrode and grounding pad results in current flow through the tissue and accompanying resistance to the current flow causes heating of the biological tissue. The power deposition is regulated with the help of control algorithm. Moreover, the control algorithm which ensures to prevent charring and overheating of the tissue also responds differently to this variation. This is due to the fact that each tissue behaves differently in terms of temperature increase and evolution of ablation volume to the external impetus provided by the RFA

* Corresponding author. Tel.: +65 6790 4455.
E-mail address: mykng@ntu.edu.sg (E.Y.K. Ng).

http://dx.doi.org/10.1016/j.ijthermalsci.2014.01.024
1290-0729/

Table 1
Electrical and thermal properties of various tissues used for analysis.

Parameter	Bone	Fat	Lung	Liver	Kidney	Muscle	Heart (myocardial)
Electrical conductivity σ [S/m]	0.022	0.01998	0.122	0.148	0.226	0.3	0.541
Thermal conductivity k [W/(m K)]	0.4	0.22	0.302	0.564	0.54	0.49	0.531
Blood perfusion rate [1/s]	0.000833	0.00035	0.0033	0.0167	0.0667	0.00045	0
Reference	[9]	[42]	[9]	[9]	[42]	[43]	[44,45]
Ablation volume V_i [m^3]	8.74E-05	1.08E-04	5.66E-05	3.44E-05	1.85E-05	1.02E-04	1.17E-04
Applied voltage V [V]	31.8	25.5	12.4	15.5	13.15	9.4	7.15

system. Apart from many factors involved which may contribute towards selection of a particular therapy from a large pool of therapies available, the efficacy of RFA can be assessed by the ablation volume/lesion size produced in the tissue.

Based on the heterogeneity of electrothermal properties encountered in biological tissues, the aim of this study was firstly to see the effect of critical parameters like thermal conductivity, electrical conductivity and blood perfusion on the radiofrequency ablation. Furthermore, instead of independent variation, the changes in parameter values across the various tissues are simultaneous. Further analysis was thus carried out to evaluate the cumulative effect of these parameters in various tissues. Ablation volumes for RFA were obtained in bone, fat, lung, liver, kidney, muscle and heart (myocardium) tissues.

The next section outlines the relevant mathematical background necessary for mathematical modelling of RFA process. Subsequent sections are dedicated to simulation setup and parametric analysis approach. Findings and observations are included in Discussion of results section and Conclusions are presented in the last section.

2. Mathematical modelling

RFA represents a coupled electrothermal problem and applies electromagnetic energy to heat the required target. Thus, the determining factor for RFA is how the electromagnetic field interacts with the biological tissue. This interaction is dependent on the size and frequency of the electromagnetic field [16]. Frequency determines the wavelength of the stimulating field and size of the object is crucial for the nature of interaction. The electromagnetic field theory is numerically coded to study the respective magnitudes of field variables which subsequently determine the amount of heat produced. Maxwell's equations that form the basis of the electromagnetic field theory are used for the determination of field variables inside the biological domain and are applicable over the whole frequency range. In full Maxwell's equations the electric and magnetic fields are coupled and call for solution of more equations requiring enhanced numerical resources. For low frequencies as are used in RFA (460 kHz), a simplified approach for Maxwell's equation known as Quasi static approach can be used. It has been reported that Quasi static approach for lower frequencies is much less rigorous and gives similar results as those by full Maxwell's equations without compromising accuracy. At lower frequencies the electric and magnetic fields are decoupled and electromagnetic field behaves in the same way as a static field does. Using the quasi static formulation, the electric field intensity E (V/m) inside the tissue can be calculated as [17]:

$$\nabla\cdot[\sigma\nabla V] = 0 \tag{1}$$

$$E = -\nabla V \tag{2}$$

$$J = \sigma\cdot E \tag{3}$$

$$Q = J\cdot E \tag{4}$$

where V is the voltage (V), σ is the electrical conductivity (S/m), J is the current density (A/m^2) and Q is the volumetric heat generation rate (W/m^3) due to electromagnetic heating.

For heat transfer in the biological tissues different mathematical models have been proposed based on the underlying methodology. These include models based on porous media theory [18], Non Fourier models [19,20], Weibaum and Jiji model [21], Wulff and Klinger continuum model [22,23] and Pennes bioheat model [24]. But Pennes bioheat model has been proven most effective because of its simplicity and effectiveness and has been adopted for the current study. Pennes model is based on the energy balance in the biological tissue with an extra term to cater to heat loss due to blood perfusion. According to Pennes the heat transfer inside the biological tissue is given as [24]:

$$\rho c\frac{\partial T(X,t)}{\partial t} = \nabla\cdot[k(X)\nabla T(X,t)] + \rho_b\omega_b c_b[T_a - T(X,t)] + Q(X,t) + Q_m(X,t) \quad X\in\Omega \tag{5}$$

where ρ is density (kg/m^3), c is specific heat (J/kg K), k is thermal conductivity (W/m K), T is temperature (K) of the tissue. ρ_b, c_b, and w_b are the density (kg/m^3), specific heat (J/kg K) and perfusion rate (1/s) of the blood respectively. T_a is the arterial blood temperature (K), $Q(X,t)$, represents the electromagnetic heat source (W/m^3) and $Q_m(X,t)$ represents the metabolic heat source. In the context of the amount of electromagnetic energy delivered in RFA, metabolic heat source can be neglected. As the system moves towards steady state, the left hand side of Eq. (5) containing time dependent term vanishes. For current study the steady state problem was solved which signifies the maximum ablation volume that can be achieved in RFA.

3. Simulation setup

The setup used for current research is shown in Fig. 1(a). Radionics cool-tip RF single needle type ablation electrode with diameter of 2 mm was modelled and rotational symmetry was utilized to minimize the memory usage [25,26]. Noticing the rotational symmetry (Fig. 1(a)), only half of the geometry was modelled. A 2D axisymmetric model was used in lieu of 3D geometry as shown in Fig. 1(b). These electrodes are minimally invasive and are planted to the desired location under image guidance from CT or MRI. In RFA the electrode is inserted to the desired location and a dispersive pad is placed elsewhere in the body which acts as ground. Voltage is applied on the active part of the electrode and desired power is delivered to avoid overheating or charring of the tissue. Application