Modeling of Radiofrequency Nerve Lesioning in Inhomogeneous Media

Nour Ismail, Sahar El Kardawy, Bassant Badwy

Abstract—Radiofrequency (RF) lesioning of nerves have been commonly used to alleviate chronic pain, where RF current preventing transmission of pain signals through the nerve by heating the nerve causing the pain. There are some factors that affect the temperature distribution and the nerve lesion size, one of these factors is the inhomogeneities in the tissue medium. Our objective is to calculate the temperature distribution and the nerve lesion size in an inhomogeneous medium surrounding the RF electrode. A two 3-D finite element models are used to compare the temperature distribution in the homogeneous and inhomogeneous medium. Also the effect of temperature-dependent electric conductivity on maximum temperature and lesion size is observed. Results show that the presence of an inhomogeneous medium around the RF electrode has a valuable effect on the temperature distribution and lesion size. The dependency of electric conductivity on tissue temperature increased lesion size.

Keywords—Finite element model, nerve lesioning, pain relief, radiofrequency lesion.

I. INTRODUCTION

FOR several years RF current has been widely used for different medical therapeutic applications, where RF-lesioning or RF-ablation, was used for the elimination of cardiac arrhythmias, destruction of tumors in different locations, and treatment of severe chronic pain and brain disorders such as Parkinson's disease [1].

RF lesioning of nerves is a procedure used to reduce certain kinds of chronic pain by irreversible thermocoagulating nervous tissue [2]. The procedure is also known as nerve ablation.

RF lesioning is based on using RF alternating current at a frequency of 500 kHz passing through neural tissue. A portion of the nerve tissue is heated by the application of the RF current via an electrode inserted adjacent to the nerve. The heat is produced by oscillating movement of ions in the tissue. This is due to the oscillating electric field around the electrode tip. This friction of ions in the tissue electrolyte produces fractional heat [2], where the temperature of the target tissue rises to (above 45-50°C).This temperature is referred to as the "lethal temperature range" and the lesion is formed. the cell structures exposed to these temperatures range for 20 seconds or more may be destroyed by the heat [3].

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The RF electrode contains a thermocouple in the tip, which is used for temperature monitoring during the lesioning and controls the current in order to keep the tip at a preset temperature, usually between 70 and 90°C [4]. For continuous/thermal RF nerve lesioning the optimal temperature of the nerve tissue is thought to not exceed 85°C alongside the nerve. This causes a long-lasting interruption in that sensory nerve or pathway and potentially reduce pain in that area [2].

Temperature is the basic lesioning parameter, where the temperature increases in the tissue creating the lesion. So it should be measured and controlled for consistent and safe RF lesioning. The final lesion size and the temperature distribution away from the electrode tip depend on specific parameters such as: the electrode tip dimensions, the electrical conductivity, thermal conductivity, and convection of the surrounding tissue. Other factor that influences the heat distribution is the inhomogeneities in the tissue medium itself [5]. Often in the applications of nerve lesioning the environment surrounding the nerve is inhomogeneous, the vascularity, differences in tissues properties, proximity to cerebrospinal fluid (CSF), bone, and other heat sinks cause irregular lesion shapes and sizes, So the effect of the inhomogeneities on the lesion size must be taken into consideration.

Finite element models applied for studying of RF heating techniques have mainly focused on cardiac ablation, tumor ablation, and cornea heating [1]. Recently finite element models have been used for simulating nerve lesioning and brain ablation. It is useful for predicting the electric field and temperature distribution in the tissue, which is an essential step in quantitative understanding of their effect on neural tissue near the electrode.

Cosman et al [3], constructed a two dimensional model to predict the spatial distribution and time dependence of electric field and thermal distributions around the electrode in a homogeneous tissue model where results were compared with ex vivo tissue data. Field predictions were made for continuous and for pulsed RF applications.

Johansson et al. [6] developed a three dimensional model of RF-lesioning in brain tissue. An axi-symmetrical model of a sphere of homogeneous grey matter with a radius of 30mm surrounded the electrode used. Their results showed the importance to investigate the influence of the thermal and electrical conductivity of the tissue, the microvascular blood perfusion and the pre-set electrode temperature and their interactions on the lesion size.

Sluijter and Kleef [7] tried to quantify the effect of a

inhomogeneous zone away from the electrode by assuming the presence of a zone of 3-mm thickness at a distance of 5 mm from the electrode tip; They studied the effect of changing the impedance, the conductivity and the washing effect in this inhomogeneous zone. Their results showed that if the inhomogeneous zone is 3 to 5mm away from the electrode the lesion becomes appreciably larger than in the homogeneous medium.

In RF nerve lesioning the environment surrounding the electrode and the target nerve is almost inhomogeneous. In this work the case of the facet joint denervation is modeled as an example of inhomogeneous medium.

The current study aims to show the influence of inhomogeneous environment surrounding the RF electrode on the lesion size and the temperature distribution. The results are compared with the homogeneous case. Also the electric conductivity as function of temperature is considered in the inhomogeneous medium and is effect on temperature distribution and lesion size is investigated.

II. METHODOLOGY

A. Description of the Theoretical Model

A 3-Dmodel describing the cervical medial branch nerve lesioning for facet joint denervation technique as shown in Fig. 1 has been constructed using a finite element program (COMSOL Multiphysics). Fig. 2 shows the geometry of the theoretical model, which consists a mono-polar RF electrode (E/ MC054.05.20), 20 gauge and an active tip length of 5mm, the target nerve and the tissues surrounding the electrode (the vertebrae, a large cylinder of muscles surrounding the model and tissue and blood perfusion in the tissue).
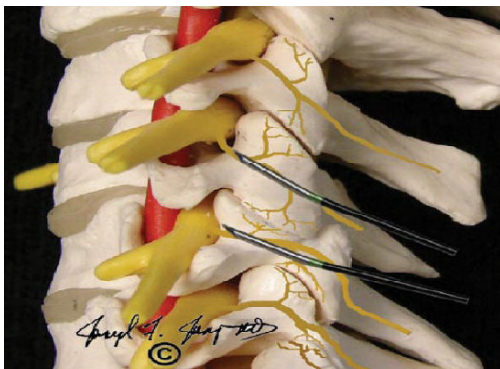

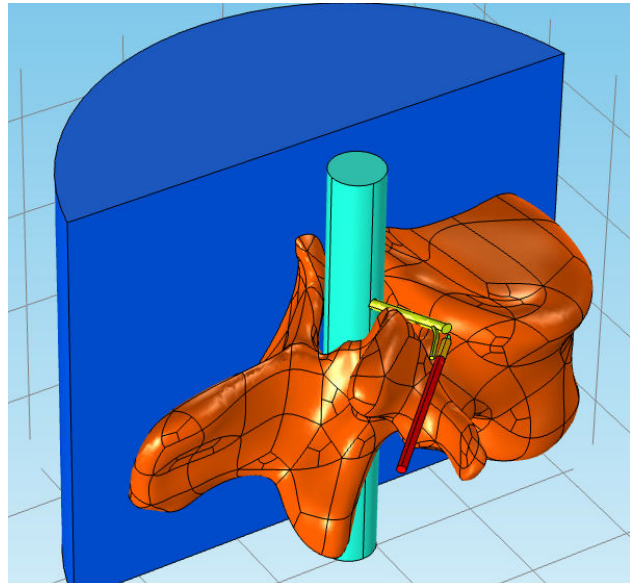Fig. 1 Medial branch nerve radiofrequency denervation [8]

Fig. 2 The geometry of the 3-D inhomogeneous finite element model

B. Governing Equation

The temperature distribution T in the tissues can be calculated using the bio-heat equation: [3]

$$\rho c_p \frac{\partial T}{\partial t} = \nabla.(k\nabla T) + q - Q_P + Q_m \qquad (1)$$

where ρ is the mass density (kg/m^3), C_p is the specific heat (J/Kg·K), ∇ is the gradient operator, k is the thermal conductivity (W/m·K), T is the temperature (K), q is the heat source (W/m^3), Q_P the heat loss from blood perfusion (W/m^3), and it is defined as:

$$Q_P = \rho_b \omega_b C_b (T - T_{amb}) \qquad (2)$$

where ρ_b the density of blood, C_b is the heat capacity of blood, ω_b is the blood perfusion rate and T_{amb} is the ambient temperature of 310 K. Q_m is the metabolic heat generation (W/m^3)and it is always ignored since it has been shown to be insignificant for RF lesioning [1], [3].

The distributed heat source q in the bio-heat equation is generated by RF power and calculated from:

$$q = J.E \qquad (3)$$

where J is the current density (A /m^2) and E is the electric field intensity (V/m).

The E-field oscillating with the RF frequency create an electric forces on mobile ions in the tissue electrolytes which in turn produce the current density vector field J within the tissue [3].

$$J = (\sigma + i\omega\varepsilon_r\varepsilon_o)E \qquad (4)$$

where, $\omega=2\pi f$ is the angular frequency, ε_r is the relative permittivity of the tissue, and $\varepsilon_o=8.85\times10^{-12}$ F/m is the permittivity of free space.

The heat source in RF lesioning is related to the electric power density [9]:

$$P = (\sigma + i\omega\varepsilon_r\varepsilon_o)|E|^2 \qquad (5)$$

The real part of power density contributes to the heating of the tissue [9]

$$q = \mathrm{Re}\{P\} = (\sigma + \omega\varepsilon'')|E|^2 \qquad (6)$$

where ε'' is the imaginary part of ε, and $(\sigma+\omega\varepsilon'')$ is defined as $\sigma_{\mathrm{effective}}$.

At low RF frequencies of 500 kHz the electric wavelength is much larger than the geometrical dimensions of interest, And the tissue impedance can be assumed to be purely resistive during heating [6]. Thus we assumed a quasi-static electrical conduction model, which allows us to solve the electric field by using Laplace's equation [10]:

$$\nabla.J = 0 \qquad (7)$$

where the electric field E can be derived by:

$$E = -\nabla V \qquad (8)$$

where V is the electric potential (V).

Two finite element models one for the homogeneous medium and the other for inhomogeneous medium are implemented in COMSOL Multiphysics, which is used for solving the above electric field and bio-heat equations. The root mean square value of RF signal and the $\sigma_{\mathrm{effective}}$ were used for solving the electric problem as a (direct-current) problem [9].

C. Characteristics of Model Elements

The electrical and thermal properties of the materials used in the model are acquired in Table I [11], [3].

TABLE I
ELECTRICAL AND THERMAL PROPERTIES OF THE MODEL MATERIALS [11], [3]

Material	Quantity	Value	Units
Nerve	ρ, density	1075	[kg/m³]
	σ, electrical conductivity	$1.11*10^{-1}$	[S/m]
	k, thermal conductivity	0.49	[W/m.K]
	C_p, heat capacity	3613	[J/kg.K]
Vertebrae	ρ, density	1908	[kg/m³]
	σ, electrical conductivity	$2.22*10^{-2}$	[S/m]
	k, thermal conductivity	0.32	[W/m.K]
	C_p, heat capacity	1313	[J/kg.K]
Muscle	ρ, density	1090	[kg/m³]
	σ, electrical conductivity	$4.46*10^{-1}$	[S/m]
	k, thermal conductivity	0.49	[W/m.K]
	C_p, heat capacity	3421	[J/kg.K]
Electrode	ρ, density	7900	[kg/m³]
	σ, electrical conductivity	$1.37*10^6$	[S/m]
	k, thermal conductivity	16.2	[W/m.K]
	C_p, heat capacity	500	[J/kg.K]
Insulators	ρ, density	800	[kg/m³]
	σ, electrical conductivity	10^{-5}	[S/m]
	k, thermal conductivity	0.01	[W/m.K]
	C_p, heat capacity	3400	[J/kg.K]
ρ_b	blood Density	1050	[kg/m³]
C_p	blood heat capacity	4180	[J/kg.K]
ω_b	blood perfusion rate	$6.4*10^{-3}$	[1/s]

D. Boundary Conditions of the Model and Initial Values

The outer surface of the model, an electrical boundary condition of V = 0, was applied to simulate the return ground electrode. The non-conducting portion of the electrode was given an insulating boundary condition such that $n.(\sigma\nabla V) = 0$; where n is the unit vector normal to the surface, σ is the electrical conductivity, and V is the voltage at the insulating surface. The thermal boundary condition for the outer surface of the cylinder surrounding the model was $T = T_{amb}$. The initial temperature was T_{amb} for the entire model. The non-conducting portion of the electrode was given a thermally insulating boundary condition $n.(k\nabla T) = 0$. An electric potential (V_o=15.5 V) was applied to the electrode tip, which is equal to the root mean square RF voltage. The simulation lasted for 60 s [1].

III. RESULTS AND DISCUSSION

Two finite element models one for the homogeneous medium and the other for inhomogeneous medium are implemented in COMSOL Multiphysics.

The 45°C temperature isosurface (45°C temperature contour) is often used to describe the expected size of the lesions and that is of importance to predict the size and shape of the lesion according to each case.

A. The Homogeneous Effect on Lesion Size

The homogeneous model consists of a cylinder of nerve tissue surrounding the RF electrode, which was constructed for comparing the results with the inhomogeneous model.

Fig. 3 shows the electric field and the temperature distribution in a homogeneous medium.

As shown in Fig. 3 (a) the maximum electric field is $4.11*10^4$ V/m and Fig. 3 (b) the maximum temperature of the tissue for the homogeneous case reaches 50.1°C.

The lesion width in the homogeneous case is equal 4.2mm as shown in Table II.

B. The Inhomogeneous Effect on Lesion Size

In order to show the effect of other tissues surrounding the nerve on the temperature distribution we constructed the inhomogeneous model close to reality.

The inhomogeneous model consists of the target nerve, the RF electrode, the vertebrae, a large cylinder of muscles surrounding the model and the blood perfusion in the tissue is considered, where the nerve diameter, the distance between bone and medial nerve surfaces and electrode dimension are close to the real dimension [12].

As shown in Fig. 4 (a) the maximum electric filed value is slightly decreased and reaches $3.28*10^4$ V/m, but the maximum temperature increased with a valuable quantity where maximum temperature reaches 82.8°C. Fig. 4 (b) shows the temperature distribution in inhomogeneous case.

As in Table II the lesion width is increased in the inhomogeneous case and equal 10.11mm, and the lesion shape becomes irregular in the side near the bone.
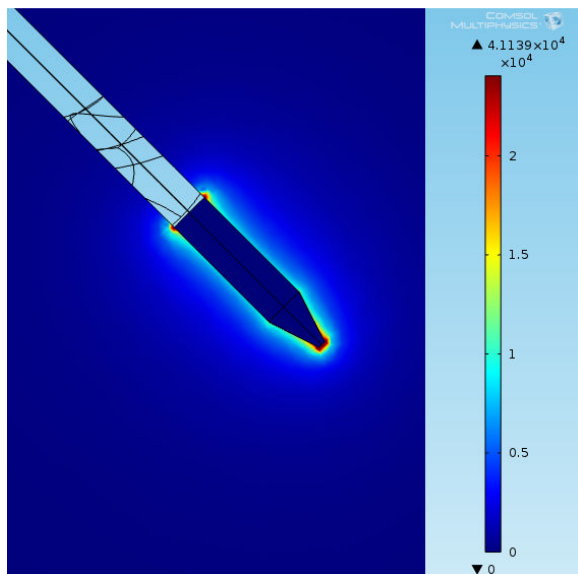

Fig. 3 (a) Electric filed distribution in homogeneous medium
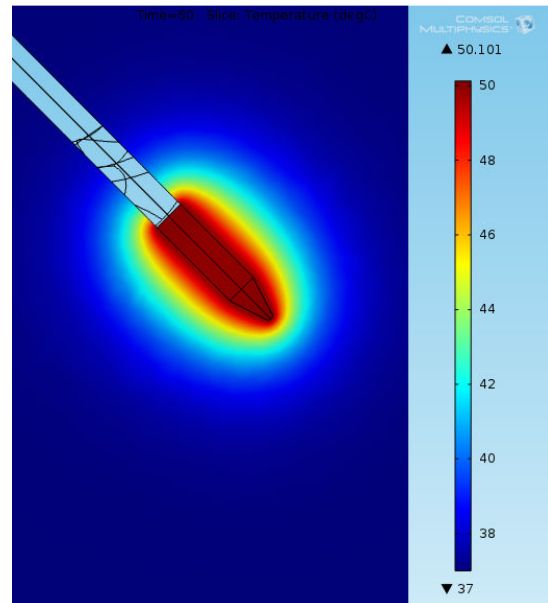

Fig. 3 (b) Temperature distribution in homogeneous medium

C. The Temperature-Dependent Electric Conductivity Effect on Lesion Size

In this section the electric conductivity was considered as a function of temperature. Where the electric conductivity depends on tissue temperature by increase 0.5% per °C above 20°C as in (9) [3].

$$\sigma(T) = \sigma + 0.0051(T - 20) \qquad (9)$$

The inhomogeneous model in Fig. 2 was used. The temperature distribution with electric conductivity as a function of temperature is shown in Fig. 5.
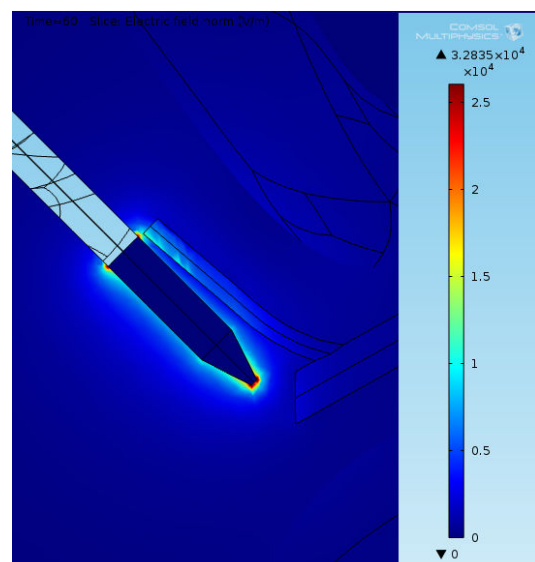

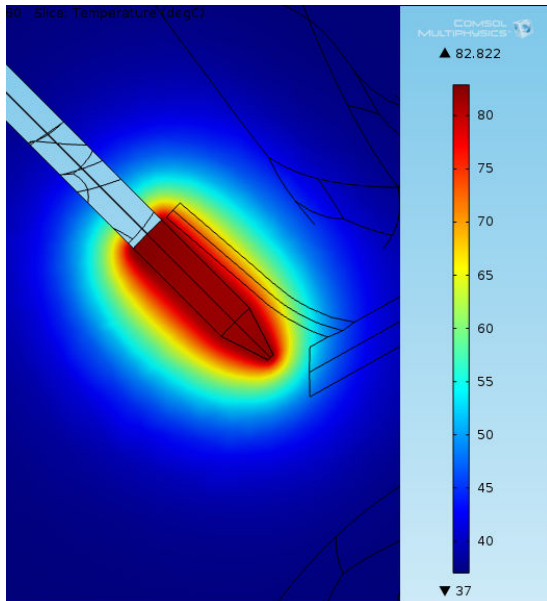Fig. 4 (a) Electric field distribution in inhomogeneous medium

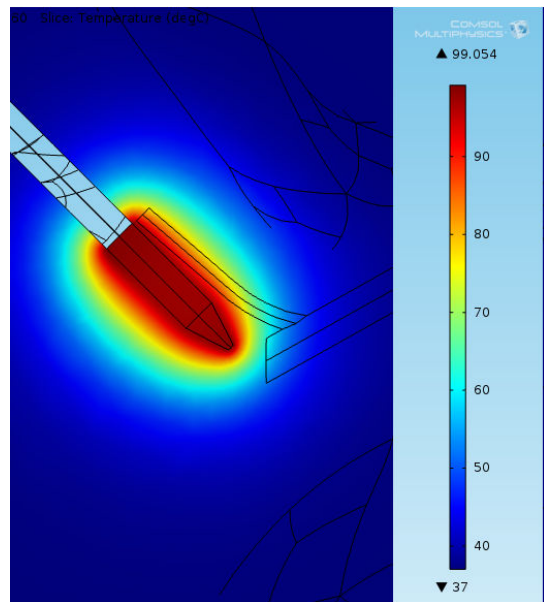Fig. 4 (b) Temperature distribution in inhomogeneous medium

Fig. 5 Temperature distribution in inhomogeneous medium with
temperature-dependent electric conductivity

It was observed that the temperature-dependent electric conductivity has an effect on the maximum temperature that cannot be ignored. The temperature rises to 99°C, while it was 82.8°C in the case of constant electric conductivity.

The lesion width is increased in the temperature-dependent electric conductivity case and equal 11.47mm as shown in Table II. Also the lesion shape becomes irregular in the side near the bone.

TABLE II
LESION WIDTH

Quantity	Case	Value [mm]
Lesion width	homogeneous	4.2
	inhomogeneous	10.11
	Temperature-dependent electric conductivity	11.47

IV. CONCLUSION

The electric field and temperature distribution due to inserting RF electrode adjacent to the medial branch nerve of the facet joint are obtained. The constructed model describes the exact inhomogeneous medium, where it composed of nerve, vertebrae, muscle and the blood perfusion effect is considered. The results obtained are more accurate than that obtained in homogeneous case. Since the inhomogeneous model is close to the real situation of RF nerve lesioning. COMSOL Multiphysics was used for constructing the models and solving the electric and bio-heat equations. The influence of tissues surrounding the target nerve can't be neglected for accurate prediction of temperature distribution and lesion size.

The study recommended further researches to build exact models for different nerves lesioning, for example dorsal ganglion, sympathetic ganglion. These different models may guide the physicians to insert the electrode accurately and achieve a safe and consistent lesion for pain relief.

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