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SKIN BURNS: NUMERICAL MODEL STUDY OF RADIO FREQUENCY CURRENT SOURCES

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INTRODUCTION

Skin burns from radio frequency (RF) current remain an important clinical consideration. The classical studies on the kinetics of skin burns in the 1940s and 1950s [1-4] continue to be the most often cited and utilized framework for their prediction and analysis. The objective of this study was to apply numerical models to more thoroughly analyze previously-described experimental skin burns created by RF current under disk electrodes [5].

The Arrhenius kinetic model for skin burns, originally suggested by Henriques and Moritz [1,2] in 1947, applies reaction kinetics to experimental data obtained form the application of heated metal blocks to pig skin:

$$\Omega(\tau) = \int_0^{\tau} A\, e^{\left[\frac{-E_a}{R\,T(t)}\right]}\, dt = ln\left\{\frac{C(0)}{C(\tau)}\right\} \qquad (1)$$

where: Ω = a dimensionless damage parameter, A = the "frequency factor" (s^{-1}), E_a = an energy barrier that molecules surmount to denature (J $mole^{-1}$), R = the gas constant (8.3143 J $mole^{-1}$ K^{-1}) and T temperature (K). The physical significance of Ω is that it is the natural log of the ratio of the original concentration of undamaged native state proteins, C(0), to the final remaining undamaged proteins at time τ (s), C(τ). In the original work, values of Ω = 0.53, 1 and 10^4 were used to demarcate 1st, 2nd and 3rd degree burns, respectively. The probabilistic formulation of damage, *P* (%) = 100[1 - exp{-Ω}], is very rarely used; but it provides substantial additional insight into the damage field. A thorough summary of skin burn analyses and numerical modeling can be found in the chapter by Diller [6].

METHODS

The numerical model was axisymmetric Finite Element Method (FEM) in Comsol 3.4 (Comsol Inc. Burlington, MA) for the stationary electric transient thermal, and damage fields. The thermal model solved the energy balance:

$$\delta_{ts}\,\rho C\frac{\partial T}{\partial t} - \nabla\bullet(k\nabla T) = \rho_b C_b w_b\left[T_b - T\right] + Q_{gen} \qquad (2)$$

where: δ_{ts} = a time-scaling term (= 1), ρ = density (kg m^{-3}), C = specific heat (J kg^{-1} K^{-1}), T = temperature (K), k = thermal conductivity (W m^{-1} K^{-1}), and Q_{gen} is the volume generation term (W m^{-3}) from RF heating. Blood perfusion effects, w (m^3 m^{-3} s^{-1}), are modeled after Pennes' method in Comsol, and the "b" subscript refers to blood. The heating times are short, however (60 s), and perfusion makes no measurable difference in the overall result.

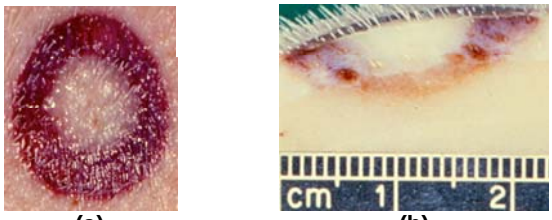
The RF heating forcing function, Q_{gen}, was determined from application of the quasi-static form of the Laplace equation:

$$\nabla\bullet\left((\sigma + j\omega\varepsilon)\nabla V\right) = 0 \qquad (3)$$

where: σ = electrical conductivity (S m^{-1}), ω = frequency (r s^{-1}), ε = electric permittivity (F m^{-1}), and V = potential (V). The electric field is determined from the solved potential field, **E** = -grad(V), and the volume power generation term for Eqn. 2 from: $Q_{gen} = \sigma\,|\mathbf{E}|^2$.

The original kinetic coefficients [1,2], A = 3.1 x 10^{98} and E = 6.28 x 10^5, do not fit the original experimental data very well: the values A = 8.73 x 10^{94} and E = 6.03 x 10^5 [7, 8] were used in this study to predict the thermal damage fields in these models. The damage calculations were performed by superposing an additional "pde coefficient" mode.

Figure 1 is the gross-histologic result from a current of 0.3 A (rms) for 60 s in a 1.6 cm diameter metal electrode on pig skin, collected three days after the experiment. The undamaged central region is surrounded by a red hemorrhagic zone that extends to a depth of 8 mm, about 4 mm into the subcutaneous fat.



(a) (b)

Figure 1. Pig skin burn from 0.3 A for 60 s, 2 cm^2 electrode (1.6 cm dia.). (a) surface (*in vivo*), (b) cross-section.

NUMERICAL MODEL RESULTS

The FEM numerical model was executed for the experiment in Fig. 1. The electrode was 6.35 mm (0.25") thick brass, and in the model, as in the experiment, it was applied at 23 °C for 15 s before RF heating — the initial skin temperature cooled to 32 °C at a depth of 0.5 mm. The tissue layer thicknesses were determined by careful analysis of Fig. 1b: 1) epidermis 1 mm, 2) subpapillary vascular plexus 0.5 mm, 3) dermis 2 mm, 4) subdermal vascular plexus 1 mm, 4) subcutaneous fat 10 mm, and 5) skeletal muscle 10 mm. The muscle layer was added to improve the electric field boundary conditions.

Table 1. Tissue electrical properties.

Tissue	σ	ε_r
Epidermis [9] (collagenous)	0.41 (l) 0.26 (t)	40*
Subpapillary Plexus *	0.65	60
Dermis [9] (collagenous)	0.41 (l) 0.26 (t)	40*
Subdermal Plexus *	0.65	60
Subcutaneous Fat [5]	0.05	10*
Skeletal Muscle [10]	0.15 (l) 0.08 (t)	500*

The electrode voltage was adjusted to 32.1 V (rms) to achieve the measured current. The ground planes were at the bottom (z_{min} = - 24.5 mm) and right hand edge (r_{max} = 30 mm) of the model space. Tissue electrical properties were determined by experiment [5, 9, 10] or estimated (*). Longitudinal (l) and transverse (t) values are given where known. The vascular plexi were estimated to be 50% blood by volume — volume mixture estimates were used in the model.

Table 2. Tissue thermal properties.

Tissue	k	ρ	C	w
Epidermis [8]	0.21	1,050*	3,700*	0.024
Subpapillary Plexus*	0.42	1,020	3,943	0.24
Dermis [8, 11]	0.31	1,050*	3,700	0.024
Subdermal Plexus*	0.42	1,020	3,943*	0.24*
Subcutaneous Fat [8, 11]	0.16	800*	3,767	0.0033
Skeletal Muscle [8, 11]	0.42	1,060	3,684	0.0022
Blood [8]	0.51	1,000	4,186	
Brass RF Electrode [12]	52	8,800	420	

Tissue thermal conductivities were extracted from mid-range values quoted in [8], as were the perfusion values for "skin" (epidermis and dermis), fat and skeletal muscle. In the vascular plexi perfusion was estimated to be 10X the resting skin value ($m^3\ m^{-3}\ s^{-1}$). Values for densities and specific heats were estimated (*) or taken from [11].

The model (Fig. 2) predicts a maximum temperature of 61 °C, which cools to 50 °C after 5 s, (49 °C measured). The numerical model results compare favorably to the experimental results. The deeper damage in the experimental cross-section is visible as an elevated temperature zone in the model.

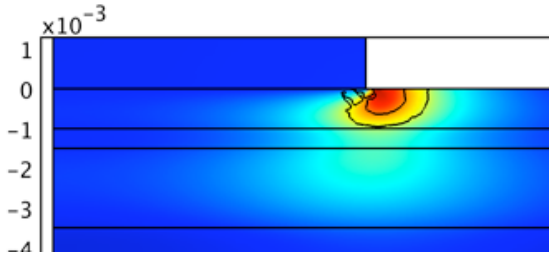


Figure 2. FEM numerical model result at t = 60 s. Temperature scale 35 - 61 °C. Damage at 10 and 90%

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