Electrical Response and Thermal Damage Assessment of Cutaneous and Subcutaneous Tissues to Noninvasive Radiofrequency Heating: A Computational Modeling Study

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Introduction

- **Epidermis**: outer cellular layer (~0.1 mm)
- **Dermis**: A dense connective tissue layer perfused with micro-vessels (~1 mm)
- **Hypodermis** (or **subcutaneous tissue**): a fine, collagenous and fibrous septa network with clusters of fat cells (1 cm to 10 cm)

- **Radiofrequency (RF) heating**
  A *non-invasive* technique can be used to produce *selective heating* of subcutaneous tissue

- **Clinical applications**
  - **Subcutaneous fat diseases**: Lipomatosis, Madelung’s disease, lipedema or cellulite
Objectives

- Model a real structure of subcutaneous tissue
- Assess the electrical and thermal effect of fibrous septa within subcutaneous tissue during RF hyperthermic heating (< 55°C)
- Quantify and compare the thermal damage occurred in two subcutaneous tissue structures (one composed by fat only and another by fat and fibrous septa)
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Mathematical modeling

- **Domain Geometry**

**MRI skin of a female** (Mirrashed, F., et al., Skin Research and Technology, 10, 2004).

**RF monopolar applicator** (Franco, W. et al. LSM 42, 2010)
Mathematical modeling

- **Governing Equations**

  - **Coupled electric-thermal problem**

    1. **Thermal problem**: Heat Transfer
       \[
       \rho c \frac{\partial T}{\partial t} = \nabla(k \nabla T) + Q_m + c_b \omega(T_b - T) + Q
       \]

    2. **Electric problem**: Electric Currents
       \[
       \nabla \sigma \nabla V = 0
       \]

  - **Thermal damage problem**

    3. **Arrhenius Equation**: Domain ODEs and DAEs
       \[
       \Omega(t) = \int_0^t A \cdot e^{\frac{-\Delta E}{RT}} dt
       \]

       - A and \( \Delta E \) for skin (Weaver and Stoll 1969)
       - \( \Omega = 1 \rightarrow \) lesion contour (transepidermal necrosis, 63% reduction in cell viability)
Boundary conditions

- Electrical conditions:
  - \( I = 0 \, A \)
  - \( V = 0 \)

- Thermal conditions:
  - \( T = 37^\circ C \)
  - \( T = 25^\circ C \)
  - \( h = 10 \, W/m^2K \), \( T_e = 25^\circ C \)

Equations:

- \( V_s(-L \leq y \leq L,0) = \left( a \left( \frac{1}{L} \right)^2 + b \right) \sqrt{PI} \)

Graph:

- The 100 W calculated curves based on 10 W and 20 W data. RMS Error at 100 W for the human equation applied to pork was ~13%.
- Recalculating coefficients based on the pig tests resulted in an RMS error of ~4% at 100 W.
Mathematical modeling

- **Thermal and electrical characteristics of the model elements**

<table>
<thead>
<tr>
<th>Element</th>
<th>$\varepsilon_r$</th>
<th>$\sigma$ (S/m)</th>
<th>$k$ (W/m·K)</th>
<th>$\rho$ (kg/m$^3$)</th>
<th>$c$ (J/kg·K)</th>
<th>$\omega$ (kg/m$^3$·s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skin</td>
<td>1832.8</td>
<td>0.22</td>
<td>0.53</td>
<td>1200</td>
<td>3800</td>
<td>2</td>
</tr>
<tr>
<td>Fat</td>
<td>27.22</td>
<td>0.025</td>
<td>0.16</td>
<td>850</td>
<td>2300</td>
<td>0.6</td>
</tr>
<tr>
<td>Muscle</td>
<td>1836.4</td>
<td>0.5</td>
<td>0.53</td>
<td>1270</td>
<td>3800</td>
<td>0.5</td>
</tr>
<tr>
<td>Septa</td>
<td>1832.8</td>
<td>0.22</td>
<td>0.53</td>
<td>1200$^*$</td>
<td>3800</td>
<td>0</td>
</tr>
</tbody>
</table>

- **Main Physical assumptions**
  - Homogeneous tissues
  - Tissues have isotropic electric and thermal properties
  - Constant $k$, $c$ and $\omega$ → variations are not significant within the 35-50°C range
  - Properties of the fibrous septa similar to those of the dermis
  - The perfusion term in the septa is neglected (i.e. fibrous septa as solid)
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Results

- Electric field

Subcutaneous tissue with fat only (no fibrous septa)

Subcutaneous tissue with fat and fibrous septa
Results

- Total electric power absorption (Q) and Electric currents (arrows)

Subcutaneous tissue with fat only (no fibrous septa)

Subcutaneous tissue with fat and fibrous septa

Time=2500  Surface: Total power dissipation density (W/mm²)
Arrow Surface: Current density (Material)
Results

- Temperature distribution and thermal damage

**Subcutaneous tissue with fat only (no fibrous septa)**

**Subcutaneous tissue with fat and fibrous septa**
Results

- Thermal damage quantification

The lesion volume is ~7 times higher considering fibrous septa.
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Conclusions

- Our results demonstrate the **importance** of including the fibrous septa when modeling RF heating of subcutaneous tissue:
  - The intensity and extent of the electric field in the subcutaneous tissue is increased considering fibrous septa network
  - Fibrous septa favors the flux of electric current → increasing the intensity of the electric field, which in turn increases power absorption within subcutaneous tissue
  - Neglecting the electric and thermal energy contributions of the fibrous septa results in underestimating thermal damage

- Our findings would be **useful** to design and develop novel devices and treatments to **subcutaneous fat diseases** during RF hyperthermic heating

**Knowledge of correct dosimetry**
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