Microwave Ablation and associated Dielectric Properties- Modelling, Measurements and Sensitivity Investigation

Mohammed Taj-Eldin, Punit Prakash

WG1/WG3 Workshop on Dielectric Properties for Novel Medical Devices: Challenges, Innovations and Opportunities

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Galway, Ireland
Presentation Outline

● Introduction
● Part 1: Microwave Ablation at 915 MHz vs. 2.45 GHz.
● Remarks
Part 1

Liver Dielectric Properties and Microwave Ablation at 915 MHz vs. 2.45 GHz
Introduction

- **Thermal ablation**: a minimally invasive technique increasingly being used for treatment of tumors in the liver, kidney, lung.

From Dodd et al., Radiographics, 20(1), 2000
Objective

- Theoretically and experimentally characterize the differences in thermal ablation with uncooled, insulated antennas, operating at 915 MHz and 2.45 using single antenna.
- 3D FEM model was implemented to simulate power deposition and transient temperature profiles during ablation at each frequency.
## Tissue Physical Properties

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Electrical properties</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Relative permittivity, $\varepsilon_r$</td>
<td></td>
<td>46.8</td>
</tr>
<tr>
<td>Effective conductivity, $\sigma$</td>
<td>S m$^{-1}$</td>
<td>0.86</td>
</tr>
<tr>
<td><strong>Thermal properties</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal conductivity, $k$</td>
<td>W m$^{-1}$ K$^{-1}$</td>
<td>0.49</td>
</tr>
<tr>
<td>Specific heat capacity, $c_p$</td>
<td>J kg$^{-1}$ K$^{-1}$</td>
<td>3370</td>
</tr>
<tr>
<td>Density, $\rho$</td>
<td>kg m$^{-3}$</td>
<td>1050</td>
</tr>
<tr>
<td>Nominal blood perfusion rate, $m_{bl}$</td>
<td>kg m$^{-3}$ s$^{-1}$</td>
<td>0, 5, 10</td>
</tr>
<tr>
<td>Specific heat capacity of blood, $c_{bl}$</td>
<td>J kg$^{-1}$ K$^{-1}$</td>
<td>3600</td>
</tr>
</tbody>
</table>

Table. Liver physical properties used in theoretical and computational Models

Dielectric Properties vs. Temperature

• Temperature-dependent changes were implemented as reported by C. L. Brace* using liver tissue.

*Experimental results (dots) of relative permittivity and conductivity versus temperature during microwave ablation. Best-fit sigmoidal curves (solid lines).

Dielectric Properties vs. Temperature

• Temperature-dependent changes were implemented as reported by C. L. Brace* using liver tissue.

Sigmoidal function adopted as the regression model, resulting best-fit equations:

\[
\varepsilon_r(T) = a_3 \left\{ \frac{1}{1 + \exp[a_1(a_2 - T)]]} \right\} + 1
\]

\[
\sigma(T) = a_3 \left\{ \frac{1}{1 + \exp[a_1(a_2 - T)]]} \right\}
\]

Regression coefficient and \( R^2 \) for figure 3.

<table>
<thead>
<tr>
<th>( a_1 )</th>
<th>( a_2 )</th>
<th>( a_3 )</th>
<th>( R^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \varepsilon_r )</td>
<td>0.0764</td>
<td>82.271</td>
<td>48.391</td>
</tr>
<tr>
<td>( \sigma )</td>
<td>0.0697</td>
<td>85.375</td>
<td>2.173</td>
</tr>
</tbody>
</table>

where temperature \( T \) is the lone independent variable (°C) and \( a_i \) (\( i = 1, 2, 3 \)) are the regression coefficients (table 3).

*Experimental results (dots) of relative permittivity and conductivity versus temperature during microwave ablation. Best-fit sigmoidal curves (solid lines), along with the upper and lower envelopes (dashed lines) used for numerical simulation.

Accuracy of the Models

Sigmoidal model more accurately predicted experimental temperatures at 2.45 GHz than previous models (mean percent differences between simulated and exp. is 4.2 %)

Electromagnetic-Thermal Simulation

- Transient tissue temperature profiles were calculated using the Pennes’ bioheat transfer equation

\[
\rho c(T) \frac{\partial T}{\partial t} = \nabla \cdot k(T) \nabla T + Q_{mw} - \omega_{bl}(T) \cdot (T - T_{bl}),
\]

where \(\rho c\) is volumetric heat capacity \([J/(m^3 \cdot ^\circ C)]\), \(T\) is temperature \( (^\circ C)\), \(k(T)\) is thermal conductivity \([W/(m \cdot ^\circ C)]\), \(\omega_{bl}(T)\) is the overall term used to describe perfusion \([W/(m^3 \cdot ^\circ C)]\), and \(T_{bl}\) is temperature of blood. Temperature dependency of volumetric heat capacity \(\rho c(T)\) incorporating tissue water vaporization

*J. Sebek et al., Medical Physics, In Press May 2016*
Results: Antenna Ablation Profiles at 915 MHz and 2.45 GHz

• After 10 min, 30 W ablation in tissue for varying perfusion levels.

Computed temperature profiles and ablation zone extents in ex vivo tissue following 30 W, 10 min ablation with a single microwave antenna operating at (a) 915 MHz and (b) 2.45 GHz. Ablation zone extents are shown for perfusion = 0, 5, and 10 kg m$^{-3}$ s$^{-1}$.
**MW Ablation Experimental Setup**

- $T_{\text{initial}} \sim 30 \, ^{\circ}\text{C}$
- $P = 30 \, \text{W}$
- Heating duration: 10 min
Experimental Validation

Fig. Illustration of ablation zone dimensions and locations of fiber optic temperature sensors during ex vivo experiments with (a) single antenna with view along the antenna axis.

S. Curto et al., Medical Physics, 42, 6152-6161, 2015
Experimental Results - Ablated Surface

• Sample ablation zones after 10 min ablations in *ex vivo* porcine muscle.

Experimentally observed (n = 4) ablation zones in *ex vivo* pork tissue following 30 W, 10 min ablation with a single microwave antenna at 915 MHz (left) and 2.45 GHz (right).
Temperature Profile during Ablation Treatment

Fig. Experimentally measured (n = 4) temperature profiles at 5 mm, 10 mm and 20 mm radially from the antenna center during 30 W microwave ablation at (a) 915 MHz and (b) 2.45 GHz in muscle.

Fig. Experimentally measured (n = 4) temperature profiles at 5 mm, 10 mm and 20 mm radially from the antenna center during 30 W microwave ablation at (a) 915 MHz and (b) 2.45 GHz in muscle.
### Experimental Results - Comparison

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<th>Tissue type and frequency</th>
<th>Height</th>
<th>Diameter</th>
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<tr>
<td>Muscle, 915 MHz, n=4</td>
<td>68.8±2.2 mm</td>
<td>29.5±0.6 mm</td>
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<tr>
<td>Liver- 915 MHz, n=3</td>
<td>72.3±6.4 mm</td>
<td>29.7±0.58 mm</td>
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<tr>
<td>Muscle, 2.45 GHz, n=4</td>
<td>56 ±5.5 mm</td>
<td>36.3±1.0 mm</td>
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<td>Liver, 2.45 GHz, n=3</td>
<td>57±3.6 mm</td>
<td>37±1.7 mm</td>
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M. Taj-Eldin, et al., APSURSI, USA, 2014

S. Curto et al., Medical Physics, 42, 6152-6161, 2015
Experimental Results - Comparison

Table. Experimentally observed (n = 4) and simulated ablation zones (in mm)

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Table. Dielectric Properties of liver vs. Muscle

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<tr>
<th>Frequency</th>
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<tbody>
<tr>
<td>Dielectric properties</td>
<td>Relative permittivity, conductivity</td>
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<tr>
<td>Liver</td>
<td>46.8, 0.86</td>
<td>43, 1.69</td>
</tr>
<tr>
<td>Muscle</td>
<td>54.99, 0.948</td>
<td>52.73, 1.73</td>
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*S. Curto et al., Medical Physics, 42, 6152-6161, 2015

**M. Taj-Eldin, et al., APSURSI, USA, 2014
Experimental and Simulated Ablation

Table 2: Experimentally observed (n = 4) and simulated ablation zones (in mm) following 5 min and 10 min single-antenna microwave ablation at 915 MHz and 2.45 GHz. d is the transversal diameter of the ablation zone, h is the height of the ablation zone, and AR is the ratio d/h

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<td>$m_{bl} = 10 \text{ kg m}^{-3} \text{s}^{-1}$</td>
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- Discrepancies of length (h), due to the assumptions of perfect electric conductors and lossless dielectrics employed in our FEM model.
- Ease the computational burden associated with discretizing good conductors at high frequencies, they neglect losses in coaxial cables and subsequent effects on heat transfer modeling.
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Part 2

Sensitivity of Microwave Ablation Models to Tissue Biophysical properties
Objective

- Computational models of microwave ablation widely used during the design optimization of novel devices and are under consideration for patient-specific treatment planning.
- Objective: assess the sensitivity of computational models of MWA to tissue biophysical properties*.

*J. Sebek et al., Medical Physics, In Press May 2016
Methodology

• Morris method employed to assess the global sensitivity of the coupled electromagnetic–thermal model, which was implemented with the (FEM) incorporated temperature dependencies of tissue physical properties.

• Variability of the model studied to characterize the size and shape of the ablation zone, as well as impedance matching of the ablation antenna.

• Sensitivity results were statistically analyzed and absolute influence of each input parameter was quantified

*J. Sebek et al., Medical Physics, In Press May 2016
Methodology

• Variability of the model studied to characterize the size and shape of the ablation zone, as well as impedance matching of the ablation antenna:

• Starting from Brace’s equations:

\[
\varepsilon_r(T) = a_3 \left\{ 1 - \frac{1}{1 + \exp[a_1(a_2 - T)]} \right\} + 1
\]

\[
\sigma(T) = a_3 \left\{ 1 - \frac{1}{1 + \exp[a_1(a_2 - T)]} \right\}
\]

• Transient tissue temperature profiles were calculated using the Pennes’ bioheat transfer equation:

\[
\rho c(T) \frac{\partial T}{\partial t} = \nabla \cdot k(T) \nabla T + Q_{mw} - \omega_{bl}(T) \cdot (T - T_{bl}),
\]

• The bioheat transfer model introduces another 7 parameters for the sensitivity study (increasing the total number of input parameters to 10), namely: (1) the baseline volumetric heat capacity \( \rho c_0 \), (2) an analogous quantity for the vaporized tissue \( \rho c_v \), (3) latent heat of liver tissue vaporization \( L \cdot C^* \), (4) temperature interval \( \Delta T \) across which the tissue changes phase, (5) thermal conductivity \( k_0 \), (6) its change with the temperature \( \Delta k \), and (7) the baseline blood perfusion rate \( \omega_{bl,0} \) at the temperature 37 C.
Highlights of Results

Average s11 coefficient sensitivity. (left) Statistically significant differences. (right) Relative influences of parameters with respect to the least influential one*.

*J. Sebek et al., Medical Physics, In Press May 2016
Most Influential Parameters

- relative permittivity, effective conductivity, and the threshold temperature at which they transitioned to lower values (i.e., signifying desiccation)
- Temperature interval across which tissues changes phase

*J. Sebek et al., Medical Physics, In Press May 2016*
Least Influential Parameters

- latent heat of tissue water vaporization and the volumetric heat capacity of the vaporized tissue

*J. Sebek et al., Medical Physics, In Press May 2016*
Conclusions

- Tissue dielectric parameters, specifically relative permittivity, effective conductivity, and the threshold temperature at which they transitioned to lower values (i.e., signifying desiccation) identified as the most influential parameters for the shape of the ablation zone and antenna impedance matching.

- Of thermal parameters, nominal blood perfusion rate and the temperature interval across which the tissue changes phase identified as the most influential.

- The latent heat of tissue water vaporization and the volumetric heat capacity of the vaporized tissue were recognized as the least influential parameters.

*J. Sebek et al, Medical Physics, In Press May 2016*
Acknowledgements

• Work was supported in part by:
  1) the National Science Foundation under grant CBET 13374382
  2) the Johnson Cancer Research Center of the Kansas State University.

Related research outputs:


Biomedical Computing and Devices Lab (BCDL)*

• Lab Research Areas:

  ➢ Model-based treatment planning tools for guiding clinical microwave ablation procedures (*accurate knowledge of tissue dielectric properties very important*).

  ➢ Integration of MW ablation/hyperthermia systems with MRI thermometry for feedback-controlled applications.

  ➢ Antenna designs offering improved spatial control of energy deposition for ablation and hyperthermia.

• Feedback/possibility for collaboration with interested parties are very welcome.

Lab Director:
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* Website: http://ece.k-state.edu/bcdl/
Questions