Microwave-induced Thermoacoustic Imaging for Radio-frequency Tumor Ablation: a Hybrid FDTD Modeling and Experimental study

Yiming Deng and Mark Golkowski
Department of Electrical Engineering
Department of Bioengineering
University of Colorado Denver

National Radio Science Meeting
Boulder, CO
January 6, 2011
Outline

- Current State of Imaging Modalities
- Thermoacoustic Imaging
- FDTD Hybrid Modeling
- Model Validation
- Applications and Future Work
Current State of Imaging Technologies

X-Ray Computed Tomography (CT)
- Relatively cheap and fast
- High radiation dosage

Positron Emission Tomography (PET)
- Can target specific radio chemicals
- Low throughput
- Exposure to ionizing radiation

Microwave Imaging
- Cheap, fast, non ionizing radiation
- Poor resolution in far field
- Little clinical use
Current State of Imaging Technologies

Magnetic Resonance Imaging (MRI)
- Great soft tissue contrast
- No ionizing radiation exposure
- “Gold standard” for clinical imaging
- Very high capital and operational costs

Ultrasound (acoustic)
- High resolution (< 1mm)
- No ionizing radiation exposure
- Cheap and portable
- Poor soft tissue contrast
Multiwave Hybrid Imaging

- Transmit one type of wave receive another
- Combine advantages, avoid disadvantages of individual modalities

**Photo-acoustic imaging**
[Xu and Wang, Rev. Sci. Instrum. 77, 2006]

**Microwave-acoustic imaging**
Microwave-Acoustic Imaging Theory

**Acoustic Wave Equation**

\[ \nabla^2 p(r,t) - \frac{1}{c^2} \frac{\partial^2}{\partial t^2} p(r,t) = -\beta_e \rho \frac{\partial^2}{\partial t^2} T(r,t) \]

**Thermal Expansion Driver**

Temperature change is driven by microwave pulse

\[ \Delta T = \frac{\sigma |E|^2 \tau}{2\rho C_p} \]

- \( p(r,t) \) : pressure
- \( T(r,t) \) : temperature
- \( E \) : microwave electric field
- \( \tau \) : duration of microwave pulse
- \( \sigma \) : conductivity
- \( \rho \) : mass density
- \( c \) : speed of sound
- \( \beta_e \) : volume expansion coefficient
- \( C_p \) : specific heat
Hybrid FDTD Code

\[
\begin{align*}
\frac{D_z^n(i,j) - D_z^{n-1}(i,j)}{\Delta t} &= \frac{1}{\sqrt{\varepsilon_0 \mu_0}} \left( \frac{H_y^n(i + \frac{1}{2}, j) - H_y^n(i - \frac{1}{2}, j)}{\Delta x} - \frac{H_x^n(i, j + \frac{1}{2}) - H_x^n(i, j - \frac{1}{2})}{\Delta y} \right) \\
\frac{H_x^{n+1}(i, j + \frac{1}{2}) - H_x^n(i, j + \frac{1}{2})}{\Delta t} &= -\frac{1}{\sqrt{\varepsilon_0 \mu_0}} \frac{E_z^{n+\frac{1}{2}}(i, j + 1) - E_z^{n+\frac{1}{2}}(i, j)}{\Delta y} \\
\frac{H_y^{n+1}(i + \frac{1}{2}, j) - H_y^n(i + \frac{1}{2}, j)}{\Delta t} &= \frac{1}{\sqrt{\varepsilon_0 \mu_0}} \frac{E_z^{n+\frac{1}{2}}(i + 1, j) - E_z^{n+\frac{1}{2}}(i, j)}{\Delta x} \\
\frac{p^{m+\frac{1}{2}}(i,j) - p^{m-\frac{1}{2}}(i,j)}{\Delta t_m} &= -\rho(i,j) \cdot c^2(i,j) \left( \frac{v_x^n(i + \frac{1}{2}, j) - v_x^n(i - \frac{1}{2}, j)}{\Delta x_m} + \frac{v_y^n(i, j + \frac{1}{2}) - v_y^n(i, j - \frac{1}{2})}{\Delta y_m} \right) \\
\frac{v_x^{m+1}(i + \frac{1}{2}, j) - v_x^m(i + \frac{1}{2}, j)}{\Delta t_m} &= -\frac{1}{\rho(i,j)} \frac{p^{m+\frac{1}{2}}(i + 1, j) - p^{m+\frac{1}{2}}(i, j)}{\Delta x_m} \\
\frac{v_y^{m+1}(i, j + \frac{1}{2}) - v_y^m(i, j + \frac{1}{2})}{\Delta t_m} &= -\frac{1}{\rho(i,j)} \frac{p^{m+\frac{1}{2}}(i, j + 1) - p^{m+\frac{1}{2}}(i, j)}{\Delta y_m}
\end{align*}
\]
Simulation Domain

- Simulation space setup to emulate recent experimental study
Simulation Video
Experimental Results

<table>
<thead>
<tr>
<th>Sol’n</th>
<th>% micro bubble</th>
<th>$\varepsilon_r$</th>
<th>$\sigma$ (S/m)</th>
<th>$v_A$ (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>14.0</td>
<td>2.32</td>
<td>1661</td>
</tr>
<tr>
<td>2</td>
<td>20</td>
<td>9.66</td>
<td>1.33</td>
<td>1730</td>
</tr>
<tr>
<td>3</td>
<td>30</td>
<td>8.34</td>
<td>1.11</td>
<td>1805</td>
</tr>
<tr>
<td>4</td>
<td>35</td>
<td>7.38</td>
<td>0.95</td>
<td>1923</td>
</tr>
<tr>
<td>5</td>
<td>40</td>
<td>6.86</td>
<td>0.84</td>
<td>2049</td>
</tr>
<tr>
<td>6</td>
<td>100</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>

- Acoustic and EM properties of solutions are different
- Higher conductivity ($\sigma$) yields greater acoustic wave amplitude.

Side by Side Comparison

- Model reproduces experimental results very well
- Experimental data is based on averages of 200 waveforms
Dielectric vs. Acoustic Effects

Experiment: acoustic and dielectric differences

Simulation: acoustic differences only

- Different waveform between solutions results from different dielectric properties
- In agreement with paper conclusions
Non-uniformity of E-field in Dielectric

Integration of $|E|^2$ over microwave pulse

Total Energy is $18065610.8933$ a.u.

- $\lambda_0 = 100$ mm; $\lambda_d = 26$ mm
- Most works assume power deposition is uniform
- Modeling and analytical solutions show that power deposition has a unique geometric signature

Petersen, Ray, Mittra, Computational Electromagnetics. 1998, p. 64
Planned Experimental Work

Ultrasound transducer
Olympus V306
\( f_c = 2.25 \text{ MHz} \)

Microwave power supply
Power: 1 kW
\( \tau < \mu\text{sec} \)
Radio Frequency ($f \sim 500 \text{ kHz}$) ablation is a clinically accepted treatment for hepatic (liver) tumors.

Tumors are destroyed through thermal heating.

Ablation using microwave sources is also being clinically investigated.

Most pressing clinical issue is lack of predictability (or real time diagnostics) of ablation size which hinders creation of treatment plans.
Investigation of ablation size as a function of blood flow

- Ultrasound to place electrode, MRI to evaluate size

Application to Ablation Treatment

- Thermo-acoustic imaging can provide cheap, portable, real time monitoring for clinical ablations.

- If microwaves are used for ablation, same hardware could provide source for thermo-acoustic imaging.

- 3-D image reconstruction algorithm needs to be implemented.

[Kruger et al., Radiology, 1999]
Conclusions

- A hybrid FDTD Ultrasound/EM simulation code for thermoacoustic imaging has been developed and validated.


- Assumption of uniformity of power deposition is shown to not be completely accurate for small dielectric structures.

- Further development of thermoacoustic imaging technique can aid in experimental ablation work and eventually be relevant in clinical ablations.