EMC/EMI Issues in Biomedical Research

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UH: close to downtown of Houston
35,066 students

ECE Department: 35 faculty members, 250 graduate students

Electromagnetic Research at University of Houston:

NSF Center For Electromagnetic Compatibility Research

Areas:
- Computational Electromagnetics
- Antennas
- High-Speed Signal Propagation
- Bioelectromagnetics
- Nano-devices
- Wireless Propagation

Faculty Members:
- 6 faculty members
- IEEE Board of Directors
- past president of AP society
- 4 IEEE Fellows
Outline

- Introduction
- Human subject models
- Methodologies in modeling
- Applications
  - Pregnant woman exposed to walk-through metal detector
  - Pregnant woman under exposure to magnetic resonance imaging
  - Safety evaluation of metallic implants in magnetic resonance imaging
  - Interactions between medical implants and vehicular mounted antennas
- Summary and future work
Introduction

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
</tr>
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<tbody>
<tr>
<td>$10^4$</td>
</tr>
<tr>
<td>extremely low frequency</td>
</tr>
<tr>
<td>power lines</td>
</tr>
</tbody>
</table>

Magnetic stimulation in human head (low frequency)

- severe depression
- auditory hallucinations
- migraine headaches
- tinnitus

Magnetic resonance imaging (radio frequency)

visualize the inside of living organisms
• The problem of human exposure to high/low frequency electromagnetic fields has been the subject of many studies.

  • Electromagnetic and temperature analysis of high-frequency exposure
  • SAR (energy deposition)
  • Temperature (thermal distribution)

  EM fields ➔ Energy deposition ➔ Tissue heating

  • Calculate induced current density and induced electric field in human body due to extremely-low-frequency exposure

  • \( J \) (current density) & \( E \) (electric field)

  EM fields ➔ Induced current ➔ Anti theft device model
Approach 1: Experimental measurement

disadvantages:
I. difficult to make models.
II. filling material is homogeneous.
III. difficult to make measurement equipments for various EM exposure.

Approach 2: Numerical simulation

CAD model + external EM source

advantages:
I. easy to make CAD models (difficult to make for experiments).
II. able to analyze inhomogeneous models
III. easy to model various external EM fields.
Human Subject Models

Models

Virtual Family Models
### Tissue parameters

#### Dielectric & thermal properties

<table>
<thead>
<tr>
<th>Tissue</th>
<th>(\rho) [kg/m(^3)]</th>
<th>(\sigma) [S/m]</th>
<th>(\varepsilon_r)</th>
<th>(\sigma) [S/m]</th>
<th>(\varepsilon_r)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Body</td>
<td>1056</td>
<td>0.49</td>
<td>52.34</td>
<td>0.51</td>
<td>46.25</td>
</tr>
<tr>
<td>Placenta</td>
<td>1058</td>
<td>0.95</td>
<td>66.30</td>
<td>1.08</td>
<td>73.19</td>
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<tr>
<td>Embryonic Fluid</td>
<td>1055</td>
<td>1.58</td>
<td>69.32</td>
<td>1.52</td>
<td>69.46</td>
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<tr>
<td>Bladder</td>
<td>1055</td>
<td>0.24</td>
<td>24.59</td>
<td>0.30</td>
<td>21.85</td>
</tr>
<tr>
<td>Bone</td>
<td>1990</td>
<td>0.06</td>
<td>16.69</td>
<td>0.047</td>
<td>14.72</td>
</tr>
<tr>
<td>Fetus</td>
<td>887</td>
<td>0.18</td>
<td>65.66</td>
<td>0.012</td>
<td>37.60</td>
</tr>
<tr>
<td>Uterus</td>
<td>1052</td>
<td>0.91</td>
<td>92.10</td>
<td>0.942</td>
<td>75.47</td>
</tr>
</tbody>
</table>

#### CAD Model (including different internal organs/tissues)

- Assign tissue parameters for each internal organs/tissues

#### Final model (realistic human body)

- Numerical simulation

### Modeling Techniques

- **Low frequency bio-electromagnetic modeling**
  - Impedance method: Induced current & electric fields
- **High frequency bio-electromagnetic modeling**
  - Finite difference time domain (FDTD) method: Specific absorption rate
- **Thermal modeling in bio-electromagnetic**
  - Finite difference solution of bio-heat equation: Temperature distribution
- **Equivalent source**
  - Generate required magnetic fields for impedance method
Method 1: Impedance method

• Impedance method
  • Efficient for ELF calculation
  • Easy to implement

Equivalent circuit network for impedance method

\[ Z_e = \frac{\Delta x}{\Delta y \Delta z (\sigma + j \omega \epsilon)} \]

Kirchhoff voltage equations

\[ \sum IZ + j \omega \mu H \cdot \mathbf{n} = V \]

\[ I^{x,j,k} = I^{x,j,k}_x + I^{y,j,k}_y - I^{x,j,k}_y - I^{y,j,k}_y \]

\[ \sum_{m=1}^{3} a^{i,j,k}_m I_s (i,j,k) = emf \cdot \mathbf{n} \]
Numerical validation example

radius = 0.25 m
\( \sigma = 0.1 \)

\( B = 1 \) Tesla
freq = 60 Hz

Method 2: FDTD

Modeling of interaction of electromagnetic fields with human bodies at high frequency

SAR (energy deposition)

Efficient numerical technique to solve electromagnetic wave problems

- Finite Difference Time Domain Method
  - Direct solution method for Maxwell’s time dependent curl equations
  - Avoids solving simultaneous equations -- matrix inversion
  - Provides for complexities of structure shape and material composition
  - Very easy to implement compared to FEM/MOM method
Method 2: FDTD

Yee’s FDTD Scheme

Explicit update scheme

- Easy to implement
- Able to be parallelized

Method 2: FDTD

Specific absorption rate (SAR) calculation

\[ SAR = \frac{\sigma |E|^2}{2\rho} = \frac{\sigma (|E_x|^2 + |E_y|^2 + |E_z|^2)}{2\rho} \]

12-field components approach

\[ E_{\text{center},i,j,k} = \frac{E_{x,i,j,k} + E_{x,i+1,j,k} + E_{x,i,j+1,k} + E_{x,i,j,k+1}}{4} \]
Method 2: FDTD

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Physical Property</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>r</td>
<td>cylinder radius</td>
<td>0.05</td>
<td>m</td>
</tr>
<tr>
<td>ρ</td>
<td>plane wave incident power density</td>
<td>1000</td>
<td>W/m²</td>
</tr>
<tr>
<td>f</td>
<td>plane wave frequency</td>
<td>2.45</td>
<td>GHz</td>
</tr>
<tr>
<td>ε</td>
<td>relative permittivity</td>
<td>47</td>
<td>-----</td>
</tr>
<tr>
<td>σ</td>
<td>conductivity</td>
<td>2.21</td>
<td>S/m</td>
</tr>
<tr>
<td>ρ</td>
<td>mass density</td>
<td>1070</td>
<td>Kg/m³</td>
</tr>
<tr>
<td>Δx</td>
<td>spatial resolution</td>
<td>0.5</td>
<td>mm</td>
</tr>
</tbody>
</table>

Method 3: Thermal modeling

- Thermal modeling/bio-heat equation

Temperature-rise computation

When a human subject in a thermal equilibrium state is exposed to EM fields, the resultant temperature rises may be obtained from thermal modeling (bio-heat equation), which takes into account such heat exchange mechanisms as heat conduction, blood flow, and EM heating.

**Bioheat transfer equation (BHTE):**

\[ C\rho \frac{\partial T}{\partial t} = K\nabla^2 T + A_0 - B(T - T_a) + Q_{EM} \]  

\[ Q_{EM} = \rho \Delta S \alpha \]  

**Boundary condition:**

\[ K \frac{\partial T}{\partial n} = -H_a(T - T_a) \]  

**Symbol** | **Physical Property** | **Units**
---|---|---
\( T \) | Temperature | °C |
\( t \) | continuous time | s |
\( s \) | surface normal | | |
\( \rho \) | mass density | Kg/m³ |
\( C \) | specific heat | | |
\( K \) | thermal conductivity | | |
\( H_a \) | convective transfer constant (for environmental ambient temperature) | | |
\( A_0 \) | basal metabolic rate | | |
\( B \) | blood perfusion constant | | |
\( m_b \) | blood mass flow rate | | |
\( T_1 \) | blood temperature (constant) | °C |
\( T_e \) | environmental ambient temperature (constant) | °C |
Method 3: Thermal modeling

Modeling procedure

- Calculation of basal temperature \( Q_{basal} \)
- Calculation of SAR \( (Q_{SAR}) \)
- Calculation of new temperature \( Q_{new} \)

Steady state solution of bio-heat equation

FDTD method for Maxwell equation

Transient solution of bio-heat equation

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Physical Property</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \rho )</td>
<td>mass density</td>
<td>1070</td>
<td>Kg/m³</td>
</tr>
<tr>
<td>( C )</td>
<td>specific heat</td>
<td>3140</td>
<td>J/(kg·°C)</td>
</tr>
<tr>
<td>( K )</td>
<td>thermal conductivity</td>
<td>0.502</td>
<td>W/(m·°C)</td>
</tr>
<tr>
<td>( H_a )</td>
<td>convective transfer constant</td>
<td>8.37</td>
<td>W/(m²·°C)</td>
</tr>
<tr>
<td>( A_0 )</td>
<td>basal metabolic rate</td>
<td>1005</td>
<td>W/m³</td>
</tr>
<tr>
<td>( B )</td>
<td>blood perfusion constant</td>
<td>1674</td>
<td>W/(m³·°C)</td>
</tr>
<tr>
<td>( T_a )</td>
<td>ambient temperature</td>
<td>24</td>
<td>°C</td>
</tr>
<tr>
<td>( T_b )</td>
<td>blood temperature</td>
<td>37</td>
<td>°C</td>
</tr>
<tr>
<td>( \Delta x )</td>
<td>spatial resolution</td>
<td>0.5</td>
<td>mm</td>
</tr>
</tbody>
</table>

Basal temperature
Final temperature
Temperature rise
Method 4: Equivalent source
Types of walk-through metal detector

Alternative Choice: Measure the magnetic field at a few planes

Method 1. X-ray the walk-through detector

Method 2. Interpolation of the measured field

Method 3. Equivalent source modeling

Each plane has a size of 120 cm in the horizontal direction and 180 cm in the vertical direction.
Method 4: Equivalent source

Equivalent source discretization and the coordinate system

Biot-Savart law

\[ \mathbf{B} = \frac{1}{\mu} \nabla \times \mathbf{A} = \frac{\mathbf{J} \times \mathbf{R}}{4\pi |\mathbf{R}|} \]

Equivalent current distribution

This equivalent may not be the exact coil configurations but it can produce the same magnetic fields as that of the real coil configuration

Method 4: Equivalent source

A numerical validation experiment

(magnetic fields generated by the two loop coils)

Measured data

least square method
Method 4: Equivalent source

Equivalent source plane
1. Size
2. Mesh density

Convergence analysis

\[
\text{relative error} = \frac{\sum |H_{\text{simulated}} - H_{\text{measured}}|}{\sum |H_{\text{measured}}|}
\]
Method 4: Equivalent source

Applications

- Pregnant woman exposed to walk-through metal detector
- Pregnant woman under exposure to magnetic resonance imaging
- Safety evaluation of metallic implants in magnetic resonance imaging
- Interactions between medical implants and vehicular mounted antennas
Application 2: Safety assessment for WTMD

Safety evaluation of walk-through metal detectors

- Walk-through metal detectors are an important part of airport security systems
- Metal detectors use the electromagnetic signal variations as a means to detect metal objects
- Standard was developed based on male models, no safety assessment was performed for pregnant women
- Induced current strength should be used for emission safety assessment (hard to directly measure the induced current strength within human subjects)

Application 2: Safety assessment for WTMD

Develop a procedure that can be used towards accurate safety assessments for walk through metal detector electromagnetic emission

Measurement of magnetic fields

Equivalent source

Evaluate induced currents (impedance method)

- Represent the original walk-through metal detector electromagnetic emission
- Able to calculate the magnetic field distribution at any points within the human subjects
- Extreme low frequency modeling
Application 2: Safety assessment for WTMD

Current density (mA/m²)

ICNIRP Limit 2.0

<table>
<thead>
<tr>
<th>Tissue Type</th>
<th>Month1</th>
<th>Month2</th>
<th>Month3</th>
<th>Month4</th>
<th>Month5</th>
<th>Month6</th>
<th>Month7</th>
<th>Month8</th>
<th>Month9</th>
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<tbody>
<tr>
<td>Bladder Tissue-averaged</td>
<td>0.18</td>
<td>0.88</td>
<td>0.17</td>
<td>0.82</td>
<td>0.17</td>
<td>0.84</td>
<td>0.17</td>
<td>0.83</td>
<td>0.46</td>
</tr>
<tr>
<td>Maximum (1cm²)</td>
<td>0.23</td>
<td>1.13</td>
<td>0.23</td>
<td>1.21</td>
<td>0.21</td>
<td>1.21</td>
<td>0.21</td>
<td>1.01</td>
<td>0.48</td>
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<tr>
<td>Body Tissue-averaged</td>
<td>0.51</td>
<td>2.24</td>
<td>0.51</td>
<td>2.24</td>
<td>0.52</td>
<td>2.24</td>
<td>0.52</td>
<td>2.25</td>
<td>0.55</td>
</tr>
<tr>
<td>Maximum (1cm²)</td>
<td>1.02</td>
<td>1.22</td>
<td>1.36</td>
<td>1.50</td>
<td>0.39</td>
<td>1.22</td>
<td>1.36</td>
<td>1.50</td>
<td>0.52</td>
</tr>
<tr>
<td>Bone Tissue-averaged</td>
<td>0.12</td>
<td>0.76</td>
<td>0.11</td>
<td>0.76</td>
<td>0.10</td>
<td>0.77</td>
<td>0.11</td>
<td>0.78</td>
<td>0.37</td>
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<td>Maximum (1cm²)</td>
<td>0.54</td>
<td>2.7</td>
<td>0.53</td>
<td>2.68</td>
<td>0.53</td>
<td>2.68</td>
<td>0.53</td>
<td>2.68</td>
<td>0.62</td>
</tr>
<tr>
<td>Fetus Tissue-averaged</td>
<td>0.34</td>
<td>1.84</td>
<td>0.31</td>
<td>1.68</td>
<td>0.35</td>
<td>1.9</td>
<td>0.32</td>
<td>1.73</td>
<td>0.28</td>
</tr>
<tr>
<td>Maximum (1cm²)</td>
<td>0.35</td>
<td>1.65</td>
<td>0.34</td>
<td>1.42</td>
<td>0.31</td>
<td>1.14</td>
<td>0.16</td>
<td>1.86</td>
<td>0.18</td>
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<td>Liquid Tissue-averaged</td>
<td>0.87</td>
<td>0.58</td>
<td>0.9</td>
<td>0.8</td>
<td>1.05</td>
<td>0.72</td>
<td>1.27</td>
<td>0.84</td>
<td>0.64</td>
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<tr>
<td>Maximum (1cm²)</td>
<td>0.82</td>
<td>0.55</td>
<td>0.9</td>
<td>0.8</td>
<td>1.04</td>
<td>0.97</td>
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<td>0.84</td>
<td>0.64</td>
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<td>Incertae Tissue-averaged</td>
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<td>0.48</td>
<td>0.56</td>
<td>0.46</td>
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<td>0.89</td>
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<td>Maximum (1cm²)</td>
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<td>0.65</td>
<td>0.85</td>
<td>1.1</td>
<td>1.04</td>
<td>1.45</td>
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<tr>
<td>Fetus Tissue-averaged</td>
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<td>1.1</td>
<td>0.54</td>
<td>1.1</td>
<td>0.54</td>
<td>1.1</td>
<td>0.54</td>
<td>1.1</td>
<td>0.54</td>
</tr>
<tr>
<td>Maximum (1cm²)</td>
<td>0.68</td>
<td>1.26</td>
<td>0.14</td>
<td>1.52</td>
<td>1.12</td>
<td>2.28</td>
<td>1.44</td>
<td>2.94</td>
<td>1.79</td>
</tr>
</tbody>
</table>
Maximum 1 cm² area-averaged current densities for fetus and surrounding tissues (liquid, placenta and uterus) could exceed the ICNIRP safety limit of 2 mA/m² beginning with the sixth month of pregnancy.

Application 3: Pregnant women exposed to MRI

Tissue protons align with magnetic field (equilibrium state)

Magnetic field

Application 3: Pregnant women exposed to MRI

Spatial encoding using magnetic field gradients

Relaxation processes

RF pulses field

Protons absorb RF energy (excited state)

Relaxation processes

Protons emit RF energy (return to equilibrium state)

NMR signal detection

Repeat

RAW DATA MATRIX

Fourier transform

IMAGE
Application 3: Pregnant women exposed to MRI

Develop simulation models including human body and MRI RF coil

Calculate EM fields inside exposed human subjects

Compute temperature rises of tissues

Normalize the simulated data and compare them with the IEC safety limit.

Methodology

Solve Maxwell’s equation by means of finite-difference time domain method

\[ \text{SAR} = \frac{|E|^2}{2\sigma} \]

Solve Bio-heat equation:

\[ \frac{\partial T}{\partial t} = k V^2 T + A_s - B(T - T_s) + \frac{SAR}{\rho c_v} \]

<table>
<thead>
<tr>
<th>MRI Operating mode</th>
<th>Whole body SAR (W/kg)</th>
<th>Local SAR_{head} (W/kg)</th>
<th>Maximum temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>2</td>
<td>10</td>
<td>39.6</td>
</tr>
<tr>
<td>First level controlled</td>
<td>4</td>
<td>10</td>
<td>39.6</td>
</tr>
</tbody>
</table>
Application 3: Pregnant women exposed to MRI

MRI RF birdcage coil model

64 & 128 MHz
Normal & first level controlled modes

Application 3: SAR and thermal results (64 MHz)

Normal mode

First level controlled mode
Based on the results of this study, we recommend **not performing MRI procedures on pregnant women using the first level controlled mode**. These results can also be used towards developing safety standards for pregnant women undergoing an MRI.

SAR and temperature rise distributions are **quite different** at the two MRI operating frequencies. Such variation is caused by the different electric field distributions generated by MRI coils at these two frequencies and it is also related to the difference in dielectric parameters at these two frequencies.
On May 10, 2005, in response to several reports of serious injuries from medical facilities around the country, the FDA issued a Public Health Notification reminding all medical personnel of the importance of properly screening patients for implanted neurological stimulators before administering an MRI.
A typical police car (Ford Crown Victoria)

CAD model of the car

Car with medal parts only

According to IEEE P1528.2

Ground is 30cm thick slab, with relative permittivity 8 and conductance 0.01 S/m, extend 10cm in x and y Direction beyond the car/bystander.

According to IEEE 1528.3 On the Ground Modeling Implementation

Three facing direction:
- Bystander model 1 --> facing the car
- Bystander model 2 --> facing front
- Bystander model 3 --> face off the car

Four seat modeling:
- Passenger model 1 --> with medal seat
- Passenger model 2 --> with spring coils
- Passenger model 3 --> with both seat & coils

Antenna
- 1/4 30 MHz
- 1/4 75 MHz
- 1/4 150 MHz
- 1/4 450 MHz
- 1/4 900 MHz
- 5/8 150 MHz
- 5/8 450 MHz
- 5/8 900 MHz

d-distance
- 20cm away
- 100cm away
Design of Implantable Antenna
Trunk mounted antenna

Passenger back center 1/4 antenna at 450MHz

Electric Field Distribution at 900 MHz
<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>SAR with Device (W/kg)</th>
<th>SAR W/O Device (W/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>150 MHz</td>
<td>0.0028</td>
<td>0.0020</td>
</tr>
<tr>
<td>450 MHz</td>
<td>0.0041</td>
<td>0.0034</td>
</tr>
<tr>
<td>900 MHz</td>
<td>0.0077</td>
<td>0.0057</td>
</tr>
</tbody>
</table>

Modeling of taser darts (5 mm into human model)

Darts at front, induced current within human models

Different color corresponds induced current strength. For example, red color corresponds to large current strength.