Approved Minutes
IEEE/ICES TC95 Subcommittee 6 EMF Dosimetry Modeling

0900 – 1200 h
Friday, 25 January 2019
Motorola Solutions, Inc., 8000 West Sunrise Blvd
Plantation, FL 33322

1. Call to Order
Chairman called the meeting to order at 0905 h.

2. Introduction of those Present
Each of the attendees introduced her/himself. (See Attachment 1 for the list of attendees.)

3. Approval of Agenda
Following a motion by Chou that was seconded by Glembo, the agenda was approved as presented (see Attachment 2).

4. Approval of the Minutes (January 2018 Meeting)
The minutes of the 24 January 2018 meeting had already been approved. Additional confirmation was taken as it was the first meeting till the last time.

5. Chairman’s Report
Hirata began the Chairman’s report on new WGs and TFs established since 2018. WG4: Exploring the electrostimulation threshold in the brain is chaired by Joseph and Gomez-Tames. TF1: ERL at Intermediate frequencies is chaired by Kashiwa. TF1 deals in how to set the exposure limit at intermediate frequencies due to significant differences between IEEE standard and 1998 ICNIRP. Overview of the active working groups and SC6 research agenda was presented. ICNIRP is preparing the LF data gap document, which has not yet been published. Finally, Hirata explained that a new WG5 was formed and chaired by El Hajj to investigate the appropriate definition of incidence power density for frequencies larger than 6 GHz.

6. Working Group Reports

New Working Group (See Attachment 3)
Walid (chair) gave a presentation introducing the new working group WG5: Definition of incident power density to correlate surface temperature elevation, with the participation of 20 members. The goal of the WG is to define incident power density. Two possible candidates are spatial-average power density flux crossing and spatial-average norm of the pointing vector. For this, physical and mathematical meaning will be addressed as well as verification using temperature elevation, analytical solutions, computational models, and measurements for different exposures scenarios. Hirata commented that normal component of incidence power density has shown a good correlation to canonical exposure but to be investigated to different antennas scenarios. Walid planned to arrange a face-to-face meeting in conjunction with the next JWG11 and JWG12 meetings in March 2019.

WG4 Report (See Attachment 4)
Co-chair of WG4, Gomez-Tames provided a progress report on the activities of WG4: Exploring the electrostimulation threshold in the brain. Ongoing activity includes studies on the consistency of E-field computation and consistency of neuronal models for brain stimulation by transcranial magnetic
stimulation exposure. Also, dosimetry and exposure reference levels were derived. Also, a presentation will be given at EMC2019 in Sapporo, and a joint-paper is under preparation. Gomez-Tames invited more groups to participate in the intercomparison. J. Patrick Reilly commented that the models do not describe all mechanism of activation, e.g., synaptic effects.

**TF1 Report** (See Attachments 5)

Kashiwa could not connect to the meeting. Hirata gave a presentation on a study published in IEEE Access by TF1. The paper revisited the relationship between SAR limits and exposure reference levels. Four research groups joined the intercomparison. Magnetic and electric field exposure were studied using anatomically realistic body models. The results show the comparison between the IEEE and ICNIRP reference levels and the values derived using computational models under various exposure scenarios.

7. **Technical Presentations**
   **Role of skin in Detailed Anatomical Modeling** (See Attachment 6)

   J. Patrick Reilly gave a presentation on modeling of skin in simulations involving detailed anatomic models. Reilly noted that IEEE C95.1 Dosimetric reference levels do not apply to currents crossing skin layers. He then reviewed the rationale of the current C95.1 standard. ERLs are derived using the Ellipsoidal Uniform Conductivity (EUC) model. He then discussed the hot spots of induced electric fields crossing the skin observed using anatomic models of the human body. He discussed that no nerve endings are crossing or terminating in the stratum corneum and argued that skin-crossing fields are not relevant to standard. Finally, he reviewed results obtained at Hirata's laboratory on percentile calculation and spatial averaging on induced electric fields. After the presentation, discussion concentrated on exposure of the limbs and partial body exposure.

   **Review of LF Numerical Artifacts** (See Attachment 7)

   Hirata presented a review of low-frequency dosimetry. He reviewed several intercomparison studies published since 2000, discussing uncertainty in the induced electric field. He also reviewed the history of the 99th percentile value in LF dosimetry. He then showed new computational data about numerical artifacts and spatial averaging of induced electric fields, and how a better agreement between different computation by different groups has been achieved.

   **On the Issues of LF Numerical Dosimetry** (See Attachment 8)

   Valerio De Santis from the University of L'Aquila gave a presentation on uncertainty caused by segmentation of anatomic models, skin models, anisotropy of muscle and nerve tissues, staircasing issues, singularity, spatial averaging, post- or preprocessing of E-fields. He also discussed the accuracy of EUC and DA model.

8. **New Business**
   Hirata and AdCom will discuss whether a new WG is needed for partial-body exposure.

9. **Time and Place of Next Meeting**
   The next SC6 meeting will be held in Aug. 8 2019.

10. **Adjourn**
   There being no further business, the meeting was adjourned at 12:02 h.
## Attendance List

**TC95 SC6 (EMF Modeling and Dosimetry): 25 January 2019, 0900-1200 h**

<table>
<thead>
<tr>
<th>Last Name</th>
<th>First Name</th>
<th>Affiliation</th>
<th>Country</th>
<th>IEEE SA Member?</th>
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<tr>
<td>Altunyurt</td>
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<td>Ford Motor</td>
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<td>Bill</td>
<td>Exponent</td>
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<td>Goga</td>
<td>Motorola Solutions, Inc.</td>
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<td>Btcher</td>
<td>Matt</td>
<td>Sublight Engineering</td>
<td>US</td>
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<tr>
<td>Chou</td>
<td>C-K</td>
<td>Independent Consultant</td>
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<td>Cvetkovic</td>
<td>Mario</td>
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<tr>
<td>De Santis</td>
<td>Valerio</td>
<td>University of L’Aquila</td>
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<td>Douglas</td>
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<td>El Hajj</td>
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Approved Agenda

IEEE/ICES TC95 Subcommittee 6 EMF Dosimetry Modeling

0900 – 1200 h
25 January 2019
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1. Call to Order
Hirata

2. Introduction of those Present
All

3. Approval of Agenda
Hirata

4. Approval of the Minutes (January 2018 Meeting)
Hirata

5. Chairman’s Reports
Hirata

6. Working Group Reports
New Working Group
El Hajj
WG4 Report
Joseph & Gomez-Tames
TF1 Report
Kashiwa & Hirata

7. Technical Presentations
Role of skin in Detailed Anatomical Modeling
Reilly
Review of LF Numerical Artifacts
Hirata
On the Issues of LF Numerical Dosimetry
De Santis

8. New Business
Hirata

9. Time and Place of Next Meeting
Hirata
Definition of incident power density to correlate surface temperature elevation

IEEE/ICES TC95/SC6 in cooperation with TC34

25/01/2019

Dr. Walid EL HAJJ
Outlines

- Scope
- Power Density Definitions
- Scientific Rationales
- Assessment of incident power density using standard antennas
- Assessment of incident power density using real devices
- Goals and expected output
Scope

Definition of incident power density in the near field is discussed to correlate surface temperature elevation in the frequency range from 6 GHz to 300 GHz by computer simulations to bridge the gap between IEEE C95.1 standard and the current activity of the JWG12. Additional scientific rationale of the incident power density in the IEEE C95.1 standard is discussed, as well as the contribution to the uncertainty originated from the measurement protocol.
PD Definitions

1. Spatial-average power density flux crossing the surface

\[ S_{n,avg}(r) = \frac{1}{2A_{av}} \int \int_{A_{av}} Re\{E \times H^*\} \cdot \hat{n}dA \]

2. Spatial-average norm of Poynting vector on the surface

- Non-physical overestimation

\[ S_{tot,avg}(r) = \frac{1}{2A_{av}} \int \int_{A_{av}} ||Re\{E \times H^*\}||dA \]

Which definitions are better correlate with temperature elevation in the tissue?
Power Density Definition

Bibliography – Physical and Mathematical meaning

- Poynting Theorem -
  - Differential and Integral form
  - Divergence Theorem
  - Energy Flux
  - Energy Transfer
- Poynting Vector
- Power Density
  - Single point or Spot Power Density
  - Spatially Averaged Power Density
    - Normal Component
    - Norm of Poynting Vector
  - Time Averaged Power Density
Scientific Rationales

- Two candidates of incident power density
  - The normal component crossing the surface
  - The norm of the Poynting vector

- Verification of two candidates:
  - Temperature elevation
  - Analytical models
  - Computational models
  - Measurement

1) \[ S_{av} = \frac{1}{T \cdot A} \int \int \mathbf{E} \times \mathbf{H} \cdot \mathbf{n} \, dA \]
2) \[ S_{av} = \frac{1}{T \cdot A} \int \int |\mathbf{E} \times \mathbf{H}| \, dA \]
Assessment with Standard Antennas
PD using Normal vs Norm of Poynting Vector

<table>
<thead>
<tr>
<th>Antenna Type</th>
<th>Frequencies (GHz)</th>
<th>Distance (mm)</th>
<th>N : Numerical * M: Measurement</th>
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<td>Dipole</td>
<td>10, 30, 60, 90</td>
<td>2, 5, 10, 50, 150</td>
<td>N</td>
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<tr>
<td>Patch</td>
<td>10, 30, 60, 90</td>
<td>2, 5, 10, 50, 150</td>
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<tr>
<td>Patch Array</td>
<td>10, 30, 60, 90</td>
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<td>Dipole Array</td>
<td>10, 30, 60, 90</td>
<td>2, 5, 10, 50, 150</td>
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<td>Slotted Array</td>
<td>10, 30, 60, 90</td>
<td>2, 5, 10, 50, 150</td>
<td>N, M</td>
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(*) Results of IEC/IEEE JWG 11 / JWG 12 measurement and modelling campaign can be used.

Examples from JWG 12 Measurement Campaign
Assessment using active device
PD using Normal vs Norm of Poynting Vector

<table>
<thead>
<tr>
<th>Device Type</th>
<th>Frequencies (GHz)</th>
<th>Distance (mm)</th>
<th>N : Numerical M: Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>WiGig Mockup</td>
<td>58.32, 60.48, 62.64</td>
<td>2, 5, 10, 50</td>
<td>M</td>
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</table>

Example from JWG 12 Measurement Campaign

(*) Results of IEC/IEEE JWG 12 measurement campaign can be used?
Goals and expected Output

- Clear Physical and Mathematical definition of Poynting vector and power density metrics
- Scientific rationales behind the choice of candidates of incident power density candidates i.e. Normal vs. Norm
- Numerical and Experimental evidences supporting the scientific rationales
- Target date: October 2019 in order to use one PD definition in the CDVs of JWG11 and JWG12.
## Participants

<table>
<thead>
<tr>
<th>Member</th>
<th>Name</th>
<th>Institution</th>
<th>Country</th>
<th>e-mail</th>
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<tbody>
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<td>Apple</td>
<td>USA</td>
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<tr>
<td>9</td>
<td>Niels Kuster</td>
<td>Speag</td>
<td>Switzerland</td>
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<td>Mark Douglas</td>
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<td>11</td>
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<td>14</td>
<td>Ae-Kyoung</td>
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<td>15</td>
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<tr>
<td>17</td>
<td>Andreas Christ</td>
<td>Speag</td>
<td>Brazil</td>
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<tr>
<td>18</td>
<td>Akimasa Hirata</td>
<td>Nagoya Institute of Technology</td>
<td>Japan</td>
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<td>20</td>
<td>Davide Colombi</td>
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</table>
IEEE/ICES TC95
Working Group 4
Exploring the electrostimulation threshold in brain

Co-chairs:
Wout Joseph (Ghent Univ., Belgium)
Jose Gomez-Tames (NITech, Japan)

Secretary
Emmeric Tanghe (Ghent Univ., Belgium)
WG4: Thresholds in CNS

WG4 created in September 17th, 2017. (SC6 EMF Dosimetry Modeling)

Co-Chair: Wout Joseph (Ghent Univ., Belgium)
Co-Chair: Jose Gomez-Tames (NITech, Japan)
Secretary: Emmeric Tanghe (Ghent Univ., Belgium)

SCOPE: Assessment of brain stimulation threshold by combined modelling of electromagnetics and CNS neuron models in LF (“axonal potential generation thresholds”).
WG4: Thresholds in CNS

WG4 members list.

Wout Joseph, Ghent Univ., Belgium
Jose Gomez-Tames, NITech, Japan
Emmeric Tanghe, Ghent Univ., Belgium
Thomas Tarnaud, Ghent University, Belgium
Antonino Mario Cassara, IT’IS Foundation, Switzerland
Ilkka Laakso, Aalto University, Finland
Tom Van de Steene, Ghent University, Belgium
Y. L Diao, South China Agricultural University, China
Alex Kent, Abbott, USA.
Peter Leung, City University, China
Akimasa Hirata, NITech, Japan
Within the general scope, WG4 considers unresolved issues raised in the research agenda of the IEEE ICES (Reilly and Hirata 2016)
Research agenda of the IEEE ICES (Reilly and Hirata 2016)

- 3.3 Consistency of excitation model
  “How do these models compare? If there are significant differences, on what basis can one be recommended over another? A recent survey among users of ES models reveals large differences in predicted excitation thresholds (Reilly 2016).”

- 3.4 Waveform sensitivity
  “How do the existing nerve excitation models compare in this respect?”

- 3.10 Validation
  “Computational ES models must be experimentally validated under some representative conditions. It is important to identify published sources of applicable experimental data, and to make comparisons with ES model predictions.”

- 4.8 Statistical models of reaction thresholds
  “The statistical distribution of experimental thresholds should be included in validation efforts.”
On-going WG4 Activities

1. Consistency of the excitation neurons for different scenarios.
   - Stimulation type (TMS)
   - Uncertainty analysis (Nerve model type, position/orientation, (An)isotropy, waveform parameters)
   - Target (cortical motor area, skin/muscle tissue)

2. Survey of experimental thresholds in neurons.
   - Statistical distribution of the experimental thresholds
WG4: Thresholds in CNS

1. Consistency of the excitation neurons for different scenarios.

Two Steps:

1. Induction Model
   - Consistency of the E-field computation
   - Consistency of the neuron models

2. Electrostimulation model (ES)
Intercomparison

- Exposure scenarios: TMS over Cz position
  - Research groups: Nagoya Institute of Technology (SPFD) and University of Ghent (FEM, Sim4Life)
  - Models: Anatomical head model (resolution of 0.5 mm, 13 tissues)
  - Frequency: 10 kHz
  - Coil Current: 1 A
  - Coil Type: Figure-8 coil of 45 mm of diameter (1 turn)

- Post-processing: 2-mm cube, 99.0, 99.9%ile value
Intercomparison: Induction Model

(TMS on Cz) (SPFD) (FEM)

EF [V/m]

0 0.3 0.6 0.9

IEEE ICES
Table 1. Computed EF strength in the gray matter for different metrics.

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<tr>
<th>Metric</th>
<th>Numerical Methods</th>
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<td><strong>SPFD [mV/m]</strong></td>
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<tr>
<td>Maximum</td>
<td>93.2</td>
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<tr>
<td>2-mm Cube</td>
<td>76.2</td>
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<tr>
<td><strong>99.9% ile</strong></td>
<td><strong>61.6</strong></td>
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<td>2-mm Cube 99.9% ile</td>
<td>58.0</td>
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<td>99 % ile</td>
<td>37.7</td>
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<tr>
<td>2-mm Cube 99 %ile</td>
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<tr>
<td>1 mm-depth</td>
<td>83.6</td>
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<td>2 mm-depth</td>
<td>74.4</td>
</tr>
</tbody>
</table>

The *in-situ* field strength values show less variation (around 59 mV/m) between the using the metrics of 99.9\textsuperscript{th} percentile and 2-mm cube adapting 99.9\textsuperscript{th} percentile.
## Table 2. Error Between Analytical and Computed Electric Field Strength in Non-uniform Exposure (WG2)

<table>
<thead>
<tr>
<th>Tissue</th>
<th>Singular Point (%)</th>
<th>Proposed (%)</th>
<th>99.9th Percentile (%)</th>
<th>99.0th Percentile (%)</th>
<th>Smoothing (%)</th>
<th>2 x 2 x 2 mm³ Cube (%)</th>
<th>Maximum (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) 0.5 mm, 60 mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Skin and fat</td>
<td>99.956</td>
<td>−3.9</td>
<td>−6.4</td>
<td>−21.4</td>
<td>7.3</td>
<td>19.4</td>
<td>29.2</td>
</tr>
<tr>
<td>Muscle</td>
<td>99.962</td>
<td>−1.5</td>
<td>−3.6</td>
<td>−17.2</td>
<td>1.5</td>
<td>5.3</td>
<td>15.3</td>
</tr>
<tr>
<td>Cortical bone</td>
<td>99.940</td>
<td>4.4</td>
<td>2.1</td>
<td>−19.2</td>
<td>7.1</td>
<td>33.1</td>
<td>46.1</td>
</tr>
<tr>
<td>Cancellous bone</td>
<td>99.964</td>
<td>−3.9</td>
<td>−6.0</td>
<td>−18.1</td>
<td>1.5</td>
<td>3.7</td>
<td>14.1</td>
</tr>
<tr>
<td>Cerebrospinal fluid</td>
<td>99.927</td>
<td>−1.4</td>
<td>−3.1</td>
<td>−19.3</td>
<td>5.0</td>
<td>18.6</td>
<td>26.6</td>
</tr>
<tr>
<td>Gray matter</td>
<td>99.939</td>
<td>−4.7</td>
<td>−7.7</td>
<td>−28.7</td>
<td>11.2</td>
<td>47.3</td>
<td>55.5</td>
</tr>
<tr>
<td>(b) 0.5 mm, 200 mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Skin and Fat</td>
<td>99.913</td>
<td>4.9</td>
<td>3.7</td>
<td>−7.6</td>
<td>8.9</td>
<td>12.7</td>
<td>30.3</td>
</tr>
<tr>
<td>Muscle</td>
<td>99.920</td>
<td>5.7</td>
<td>4.8</td>
<td>−5.9</td>
<td>2.8</td>
<td>11.4</td>
<td>16.2</td>
</tr>
<tr>
<td>Cortical bone</td>
<td>99.954</td>
<td>22.3</td>
<td>18.1</td>
<td>−4.0</td>
<td>7.1</td>
<td>30.4</td>
<td>45.7</td>
</tr>
<tr>
<td>Cancellous bone</td>
<td>99.922</td>
<td>−0.2</td>
<td>−0.9</td>
<td>−7.5</td>
<td>2.8</td>
<td>4.3</td>
<td>15.0</td>
</tr>
<tr>
<td>Cerebrospinal fluid</td>
<td>99.922</td>
<td>6.1</td>
<td>4.7</td>
<td>−7.6</td>
<td>6.0</td>
<td>12.8</td>
<td>27.3</td>
</tr>
<tr>
<td>Gray matter</td>
<td>99.889</td>
<td>−0.6</td>
<td>0.9</td>
<td>−13.3</td>
<td>12.0</td>
<td>41.0</td>
<td>54.8</td>
</tr>
</tbody>
</table>

**Analytical**

**Computed**

(no processing)
CNS Thresholds

◆ Exposure scenarios:
Research groups: Independent implementations of spatially extended non-linear node (SENN) using CRRSS model
- Nagoya Institute of Technology (Nitech)
- University of Ghent (SENN-M, SENN-MA)
Models: One head model (0.5 mm, 13 tissues)
Frequency: 10 kHz
Coil Current: 1 A
Coil Type: Figure-8 coil of 45 mm of diameter (1 turn)

◆ Intercomparison of TMS-induced EF activation for fast-conducting thickly myelinated pyramidal fibers for corticospinal tracts (Betz cell’s axon).
CNS Thresholds

(A) TMS exposure over the hand motor hand
(B) Activation of sixty-three fibers projecting from the motor hand.
## Table 3. Summary of Nerve Model Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Sym</th>
<th>Nitech</th>
<th>SENN-M</th>
<th>SENN-MA</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer diameter</td>
<td>D</td>
<td></td>
<td>10 to 15</td>
<td></td>
<td>[μm]</td>
</tr>
<tr>
<td><strong>Inner diameter</strong></td>
<td>d</td>
<td>0.64D</td>
<td>0.64D</td>
<td>0.7D</td>
<td></td>
</tr>
<tr>
<td>Internodal length</td>
<td>L</td>
<td>100D</td>
<td>100D</td>
<td>100D</td>
<td></td>
</tr>
<tr>
<td>Ranvier node length</td>
<td>l_m</td>
<td>1.5 × 10⁻⁴</td>
<td>1.5 × 10⁻⁴</td>
<td>2.5 × 10⁻⁴</td>
<td>[cm]</td>
</tr>
<tr>
<td>No. of myelin layers</td>
<td>N_m</td>
<td>75 × 10⁴D</td>
<td>75 × 10⁴D</td>
<td>(Perfect myelin)</td>
<td></td>
</tr>
<tr>
<td>Axoplasmatic resistivity</td>
<td>ρ_a</td>
<td>0.07</td>
<td>0.07</td>
<td>0.11</td>
<td>[kΩ·cm]</td>
</tr>
<tr>
<td>Extracellular resistivity</td>
<td>ρ_e</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>[kΩ·cm]</td>
</tr>
<tr>
<td>Myelin conductance/layer</td>
<td>g_i</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>[mS/cm²]</td>
</tr>
<tr>
<td>Membrane capacitance</td>
<td>e_m</td>
<td>1</td>
<td>1</td>
<td>2.5</td>
<td>[μF/cm²]</td>
</tr>
<tr>
<td>Sodium conductance</td>
<td>g_Na</td>
<td>1445</td>
<td>1445</td>
<td>1445</td>
<td>[mS/cm²]</td>
</tr>
<tr>
<td>Leak conductance</td>
<td>g_l</td>
<td>128</td>
<td>128</td>
<td>128</td>
<td>[mS/cm²]</td>
</tr>
<tr>
<td>Natrium Nernst potential</td>
<td>E_Na</td>
<td>115</td>
<td>115</td>
<td>115</td>
<td>[mV]</td>
</tr>
<tr>
<td>Leak Nernst potential</td>
<td>E_l</td>
<td>-0.01</td>
<td>-0.01</td>
<td>-0.01</td>
<td>[mV]</td>
</tr>
<tr>
<td>Probability for opening the ionic channels</td>
<td>m_0</td>
<td>0.003</td>
<td>0.003</td>
<td>0.003</td>
<td></td>
</tr>
<tr>
<td></td>
<td>h_0</td>
<td>0.75</td>
<td>0.75</td>
<td>0.75</td>
<td></td>
</tr>
<tr>
<td>Temperature</td>
<td>T</td>
<td>37</td>
<td>37</td>
<td>37</td>
<td>[°C]</td>
</tr>
<tr>
<td>Segments/section</td>
<td></td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Boundary conditions</td>
<td></td>
<td>Clamped</td>
<td>Clamped</td>
<td>Clamped</td>
<td></td>
</tr>
<tr>
<td>Discretization Time step</td>
<td></td>
<td></td>
<td>min(25 μs,T_p/75)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solver</td>
<td></td>
<td>ode15s VSVO</td>
<td>Staggered Crank-Nicholson</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Length</td>
<td></td>
<td></td>
<td>1.5 – 2.5</td>
<td>[cm]</td>
<td></td>
</tr>
</tbody>
</table>
CNS Thresholds

The \textit{in-situ} EF (99.9\textsuperscript{th} percentile) on the gray matter of the hand motor area was between 100 V/m and 200 V/m for activating axons with lower thresholds.
CNS Thresholds

- Agreement between independent model implementations (10% of error)
- Large variation effect for Ranvier node length, axoplasmatic resistivity, and membrane capacitance. Sensitivity variation was less significant to myelin representation.
CNS Thresholds

- In the case of cathodal point electrode 5 mm from center NoR, the relative difference of the threshold was < 0.3 %
- The difference may be due to more sensitive variations of the electric potential along bent axon of large fibers.
Exposure scenarios
Research groups:
Uniform Exposure: lateral–medial direction
Models: One head model (0.5 mm, 13 tissues)
Frequency: 1, 10, 100 kHz kHz
Coil Current: 1mT
The derived reference level showed that allowable external magnetic field strength and *in-situ* EF established by both guidelines/standards are significantly lower than the ones computed using biophysical model of the central nervous system for medical application of TMS. Study by Laakso Group (Soldati et. al 2019 PMB) provides similar results.
Conclusion and next steps

- First intercomparison study using electrostimulation models (Nitech and U. Ghent).
- EMC2019 Sapporo Conference presentation
- Paper to be submitted (Alto U. will participate and we are open for more groups to participate).
- Detailed multi-compartmental representations of the dendritic tree and axon collaterals
- Experimental measurements (pain and motor thresholds)
Thank you
Relationship of External Field Strength with Local and Whole-body Averaged SAR for Intermediate Frequency Exposure

T. Kashiwa, K. Taguchi,
Relationship of External Field Strength With Local and Whole-Body Averaged Specific Absorption Rates in Anatomical Human Models

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ABSTRACT The International Commission on Non-Ionizing Radiation Protection (ICNIRP) guidelines and the IEEE C95.1 standard are currently under revision. In the guidelines/standard, the dominant effect for electromagnetic field exposures at frequencies above 100 kHz is the thermal effect. The whole-body- and 10g-averaged specific absorption rates (SARs), which are surrogates for core and local temperature elevations, respectively, are set as metrics for exposure evaluation. The external field strengths or incident power density, corresponding to the limit for SARs, are also used as metrics for practical compliance purposes. Although the limits for the SARs are identical amongst the guidelines/standard, the limits for the external field strengths differ by a factor of 7.4–12.9 in an intermediate frequency range (100 kHz–100 MHz). Due to the fact that the standard/guidelines were published before the computation with anatomical human models was available, it is worth revisiting the relationship between the SARs and external field strengths by computations using the human models. Intercomparison using different numerical codes was also performed to verify the results. For the main finding, as expected, the 10g-averaged SAR was a less restrictive factor for whole-body exposure over the frequencies considered in this paper. It was also found that the relationship between SARs and external field strength was satisfied, but was more conservative in the ICNIRP guidelines, whereas there were slight discrepancies below 30 MHz in the IEEE standard. The computational results would be useful for revising the permissible external field strength based on scientific results.
Background

• In an intermediate frequency range (100 kHz to 100 MHz), although the SAR limits are identical amongst the guidelines/standard, the ERL for the external field strengths differ by a factor of 7.4–12.9.

• Due to the fact that the standard/guidelines were published before the computation with anatomical human models was available, it is worth revisiting the relationship between the SARs and external field strengths.

• In the report, the relation between the SAR limits and the ERL*1 is revisited by computations using anatomical human models.

*1ERL: Exposure Reference Level (RL: Reference Level)
Research groups joining inter-comparison

- Kitami Institute of Technology
  Submitted data: Plane wave exposure
  Computational method: FDTD method

- Aalto University
  Submitted data: Uniform E field
  Computational method: FEM method

- Nagoya Institute of Technology, South China Agricultural University
  Submitted data: Uniform H field
  Computational method: SPFD*¹ method

- NICT
  Submitted data: Uniform H field
  Computational method: impedance method
SAR limits, human model, and exposure direction

**SAR limits**

- WBA SAR: 0.08 W/kg
- Local SAR: 2 W/kg (Head & Trunk)
  - 4 W/kg (Limb)

**Human model**

<table>
<thead>
<tr>
<th>Name</th>
<th>Height [m]</th>
<th>Weight [kg]</th>
<th>Number of Tissues</th>
</tr>
</thead>
<tbody>
<tr>
<td>TARO</td>
<td>1.73</td>
<td>65</td>
<td>51</td>
</tr>
<tr>
<td>HANAKO</td>
<td>1.61</td>
<td>53</td>
<td>51</td>
</tr>
<tr>
<td>NORMAN</td>
<td>1.76</td>
<td>73</td>
<td>37</td>
</tr>
<tr>
<td>Duke</td>
<td>1.74</td>
<td>70</td>
<td>77</td>
</tr>
<tr>
<td>Thelonious</td>
<td>1.17</td>
<td>20</td>
<td>73</td>
</tr>
</tbody>
</table>

- TARO is used as basic model.
- Other models are used for variability in different models.
- Spatial increment: $\Delta = 2.0$ mm

**Exposure direction**

- **Magnetic field** (3 directions)
  - Free space

- **Electric field** (AP only)
  - Grounded and free space

- **Plane wave** (AP only)
  - Grounded and free space

*1 AP: Anterior Posterior, *2 LAT: Lateral
1) Magnetic Field Exposure

- TARO model

The WBA-SAR was more restrictive than local SAR, though were comparable in the AP direction.
- The worst case for TARO is in the AP direction.

Relation between SAR limits and computed ERL

![Graph a) WBA-SAR](image1)

![Graph b) local SAR](image2)
Relation between SAR limits and computed ERL

1) Magnetic Field Exposure

- Various human models (AP direction)

- The WBA-SAR increases for models with larger height and weight.
- The SAR in the child model was much smaller than that in the adult.
- The ERL of magnetic field in ICNIRP 1998 may be over-conservatism.
2) Electric Field and Plane-wave Exposure

- TARO model (AP direction)

- The WBA-SAR is a more restrictive factor to set the RL in free space.
- But not for the grounded case, especially below 30 MHz where the SAR in the limb becomes more restrictive.
Relation between SAR limits and computed ERL

2) Electric Field and Plane-wave Exposure

• Various human models on the ground plane (AP direction)

- The curves have a bottom at approximately 30 MHz.
- The Duke model has a high local SAR due to the contact condition of the sole.
- Except in Duke model, some discrepancy were observed below 30 MHz.
3) Limb Current for Plane-wave Exposure

- Various human models on the ground plane (AP direction)

- The discrepancy was observed only for the Duke model.
Conclusion

• The local SAR was a less restrictive factor for whole-body exposure over the frequencies considered in this study.

• The ERL of magnetic field in ICNIRP 1998 may be over-conservatism.

• The ERL of electric field strength was satisfied, but was more conservative in the ICNIRP guidelines, whereas there were slight discrepancies below 30 MHz in the IEEE standard.

• The computational results would be useful for revising the permissible external field strength based on scientific results.

Relationship paper:

Role of Skin in Detailed Anatomical Modeling

J. Patrick Reilly
(jpreilly@erols.com)

Metatec Associates
12516 Davan Drive
Silver Spring, MD 20904
USA

Presented at
ICES TC95 Winter Meeting
January 25, 2019
Plantation FL, USA
### Table 1 of IEEE C95.1, DRLs 0 Hz to 5 MHz

<table>
<thead>
<tr>
<th>Exposed tissue</th>
<th>Frequency $f_e$ (Hz)</th>
<th>Persons in unrestricted environments $E_0$ (V/m)</th>
<th>Persons permitted in restricted environments $E_0$ (V/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brain $^b$</td>
<td>20</td>
<td>$5.89 \times 10^{-3}$</td>
<td>$1.77 \times 10^{-2}$</td>
</tr>
<tr>
<td>Heart</td>
<td>167</td>
<td>0.943</td>
<td>0.943</td>
</tr>
<tr>
<td>Limb</td>
<td>3350</td>
<td>2.10</td>
<td>2.10</td>
</tr>
<tr>
<td>Other tissues</td>
<td>3350</td>
<td>0.701</td>
<td>2.10</td>
</tr>
</tbody>
</table>

**NOTE**—Tabulated values are given as rms quantities.

---

DRLs in Table 1 do not apply to induced fields or current crossing skin-to-skin contact (see B.2.1.2.2.2.)
DRLs in Table 1 do not apply to current crossing skin layers. A high-resolution detailed anatomic (DA) model could potentially show exceptionally high induced fields in low conductivity layers of the skin (e.g., stratum corneum or sub-dermal adipose tissue) through which current or the induced E-field passes radially across layers of skin. ... In such cases ... criteria have not yet been developed for application to ES-based standards.
MPE levels 0 Hz – 5 MHz
(Derived from DRLs using EUC model)

Table 2
MPE limits; Whole Body Exposure.

<table>
<thead>
<tr>
<th>Frequency range (Hz)</th>
<th>Persons in unrestricted environments</th>
<th>Persons permitted in restricted environments</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B (mT)</td>
<td>H (A/m)</td>
</tr>
<tr>
<td>&lt; 0.153</td>
<td>118</td>
<td>9.39 x 10^4</td>
</tr>
<tr>
<td>0.153 to 20</td>
<td>18.1/f</td>
<td>1.44 x 10^4/f</td>
</tr>
<tr>
<td>20 to 751</td>
<td>0.904</td>
<td>719</td>
</tr>
<tr>
<td>751 to 3.35 x 10^3</td>
<td>687/f</td>
<td>5.47 x 10^5/f</td>
</tr>
<tr>
<td>3.35 x 10^3 to 5 x 10^6</td>
<td>0.205</td>
<td>163</td>
</tr>
</tbody>
</table>

Table 3
MPE Limits – Limb Exposures Only

<table>
<thead>
<tr>
<th>Frequency range (Hz)</th>
<th>Persons in unrestricted environments</th>
<th>Persons permitted in restricted environments</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B (mT)</td>
<td>H (A/m)</td>
</tr>
<tr>
<td>&lt; 10.7</td>
<td>353</td>
<td>2.81 x 10^5</td>
</tr>
<tr>
<td>10.7 to 3350</td>
<td>3790/f</td>
<td>3.02 x 10^6/f</td>
</tr>
<tr>
<td>3350 to 5 x 10^6</td>
<td>1.13</td>
<td>900</td>
</tr>
</tbody>
</table>
Modes of neural stimulation.

Nerve end organs:
Sensory receptors (illustrated), Nerve/muscle junctions. (Responds to E-field @ terminus)
Assumed mode in C95.1

Bends in neural trajectory, esp. sharp bends. (Responds to E-field @ bend)

Near electrode, or sharp conductive discontinuity. (Responds to spatial gradient of E-field)

Source: Reilly (1998)
Monophasic & Biphasic Strength-Duration Curves (SENN Model)

Fig. 3.6 of Reilly & Diamant, 2011

FD = 20 μm

Threshold electric field (V/m-pk)

Phase duration (ms)
Strength-Frequency Curves (Derived from SENN Model)

**S-F & S-D parameters related:**

\[ f_e = \frac{1}{2\tau_e} \]

rheobase (S-F) = rheobase(S-D)

FD = 20 \( \mu \text{m} \)
# Rheobase thresholds: Excite @ fiber terminus

<table>
<thead>
<tr>
<th>Fiber Diameter (μm)</th>
<th>Rheobase Threshold (V/m)</th>
<th>Modeled as most sensitive in tissue</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>6.15</td>
<td>PNS</td>
</tr>
<tr>
<td>10</td>
<td>12.3</td>
<td>CNS</td>
</tr>
</tbody>
</table>

**Conditions**
- Constant E-field along fiber axon.
- Fiber aligned with E-field
- Peak E-field values – converted to rms in standard for sinusoidal waveforms
Ellipsoidal Uniform Conductivity (EUC) Model

Example exposure: 100 T/s.

Numbered locations: Induced E-field in V/m.
EUC Magnetic Field Induction Models

- Uniform conductivity medium within loops

- Used to relate induced electric field to external magnetic field
In-situ Electric Field Display

Induced E-fields from whole body EMF.

Hot spots at skin-crossing field regions

Source: V De Santis & XL Chen (2015)
Skin-Crossing Hot Spots

❖ Whole body exposure
  ● Arm pits
  ● Crotch
  ● Skin folds
  ● Extended arms w/touching fingers

❖ Limbs
  ● Armpits
  ● Crotch
Skin-Crossing Induced Fields.

From De Santis and Chen, JPhysD, May 2014
Structure of Skin

Fig. 2.5 of Reilly (1998)
Sensory innervation in skin

From De Santis and Chen, JPhysD, May 2014
Skin crossing fields not relevant


- Skin-crossing fields are not relevant to standard.
  - Large induced E-field in stratum corneum.
  - Highly limited spatial extent
  - Neurons do not cross or terminate in corneum.
  - Excitation not sensitive to spatially limited E-fields.
  - Skin crossing fields can result in overly conservative compliance tests if spatial maximum is used

- They are NOT artefacts in DA model results

- C95.1 specifies 5 mm linear spatial average to mitigate.
Relevant questions re Detailed Anatomical Models

- Are Induction factors influenced by skin-crossing fields in DA models applied to revised C95.1?
  - Whole body exposure (arm pits; crotch; skin folds).
  - Limb only exposure (arm pits, crotch).
- Need to relate spatial maximum E-field to specific anatomical region.
- Quantify degree of conservatism if skin crossing field is involved.
- How should skin be represented in DA models?
  - Conductivity of layers; hydration
  - Layer thickness practical resolution constraints
Proposed mitigation measures re skin-crossing fields in DA models

- Spatial averaging
  - 5 mm induced E-field average per C95.1
  - Selective where skin-crossing exists (?)
- Maximum 1% exclusion rule as advocated for stair-casing artefacts.
- Adjustment of limb exposure (partial body exposure).
- Adjustment of skin conductivity specs.
- Manual editing of DA results.
Numerical uncertainty in LF Dosimetry

Katsuaki Aga, Jose Gomez-Tames, Akimasa Hirata
Nagoya Institute of Technology, Japan

Distributions of high electric field (TARO 1 mm)
**Voxel in-situ electric field value**

Maximum voxel value of *in-situ* E-Field [mV/m]

<table>
<thead>
<tr>
<th>Percentile [%]</th>
<th>2 mm(^3) Avg.</th>
<th>5 mm Avg.</th>
<th>Original</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Duke (2 mm)</td>
<td>TARO (2 mm)</td>
<td>TARO (1 mm)</td>
</tr>
<tr>
<td>100</td>
<td>61.4</td>
<td>29.1</td>
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<td>99.9</td>
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**Metrics for evaluation**

- **ICNIRP**: Averaged over a 2-mm cube (adapting 99%ile value)
  
- **IEEE**: Averaged over a *straight line segment* of 5 mm length oriented in any direction

>> In TARO(1 mm), it was averaged with the electric field of 8 voxels and converted to those of 2 mm size. In TARO(0.5 mm), it was averaged with 64 voxels.
Need for Clarification: Primary Exposure to Limbs

Induced E-fields from whole body EMF.

Hot spots at skin-crossing field regions

For Limb exposure. ERLs (Table 3 of C95.1), need to determine max. induced field in limbs without contribution of torso exposure.

Source: V De Santis & XL Chen (2015)
Mag. Field MPEs (IEEE) and RLs (ICNIRP)
IEEE-2002; -2014 & ICNIRP-2010
Basic Restrictions
IEEE-2002; 2014 & ICNIRP-2010

![Graph showing internal electric field strength vs. frequency (Hz)]
LF Dosimetry Review

K. Aga A. Hirata and J. Gomez-Tames (Nagoya Inst. Tech.)
K. Yamazaki (CRIEPI)
Inter-Laboratory Comparison of Numerical Dosimetry for Human Exposure to 60 Hz Electric and Magnetic Fields

M.A. Stuchly,¹ and O.P. Gandhi²

¹Department of Electrical & Computer Engineering, University of Victoria, Victoria, BC V8W 3P6 Canada
²Department of Electrical Engineering, University of Utah, Salt Lake City, Utah

In recent years, with the availability of high resolution models of the human body, numerical computations of induced electric fields and currents have been made in more than one laboratory for various exposure conditions. Despite the verification of computational methods, questions are often asked about the reliability of these data. In this paper, computational results from two laboratories that presented data in compatible formats are compared, supplemented with additional data from the third laboratory. Two exposures to uniform fields at 60 Hz are evaluated. The human body models used in the computations are different and so are the computational methods and codes. There are some differences in the conductivity values used for some of the tissues, as well. The results of the comparison confirm that these data are reliable, as the overall agreement is reasonably good and the differences can be rationally explained. This comparison also underscores the importance of accurate data on the dielectric properties of tissues. Bioelectromagnetics 21:167–174, 2000. © 2000 Wiley-Liss, Inc.
Intercomparison Study for ELF Dosimetry

- Stuchly and Gandhi conducted intercomparison for the data by three groups; Dimbylow (HPA, former NRPB), Gandhi (Utah Univ.), Stuchly(Univ. Victoria).

- Even though Dimbylow’s data are based on the computation for high-resolution human model (2mm), the human models used by Gandhi and Stuchly were rather coarse (6 mm and 3.6 mm) to focus on induced fields in the central nerve tissues.

Measures used for comparison

- Organ-averaged E-field (Stuchly and Gandhi)
- Organ-averaged current density (electrical conductivities did not match) (Stuchly and Gandhi)
- Maximum current density (Dimbylow and Stuchly)

Attention was not paid to the induced quantities in the central nerve tissues (ICNIRP, 1998)
Review on ELF dosimetry by Yamazaki

INTERCOMPARISON OF INDUCED FIELDS IN JAPANESE MALE MODEL FOR ELF MAGNETIC FIELD EXPOSURES: EFFECT OF DIFFERENT COMPUTATIONAL METHODS AND CODES

Akimasa Hirata1,*, Kenichi Yamazaki2, Shoji Hamada3, Yoshitsugu Kamimura4, Hiroom Tarao5, Kanako Wake6, Yukihisa Suzuki7, Noriyuki Hayashi8 and Osamu Fujiwara1

1Department of Computer Science and Engineering, Nagoya Institute of Technology, Nagoya, Japan
2Central Research Institute of Electric Power Industry, Yokosuka, Japan
3Department of Electrical Engineering, Kyoto University, Kyoto, Japan
4Department of Information Science, Utsunomiya University, Utsunomiya, Japan
5Department of Electrical and Computer Engineering, Kagawa National College of Technology, Takamatsu, Japan
6EMC Group, National Institute of Information and Communications Technology, Koganei, Japan
7Department of Electrical and Electronic Engineering, Tokyo Metropolitan University, Hachioji, Japan
8Department of Applied Science for Electronics and Materials, Kyushu University, Kasuga, Japan

Received August 17 2009, revised October 1 2009, accepted October 5 2009

The present study provides an intercomparison of the induced quantities in a human model for uniform magnetic field exposures at extremely low frequency. A total of six research groups have cooperated in this joint intercomparison study. The computational conditions and numeric human phantom including the conductivity of tissue were set identically to focus on the uncertainty in computed fields. Differences in the maximal and 99th percentile value of the in situ electric field were less than 30 and 10% except for the results of one group. Differences in the current density averaged over 1 cm² of the central nerve tissue are 10% or less except for the results of one group. This comparison suggests that the computational uncertainty of the in situ electric field/current density due to different methods and coding is smaller than that caused by different human phantoms and the conductivities of tissue, which was reported in a previous study.
Max and 99th percentile value of E-field in TARO model

Figure 2. Relative difference in maximal value of *in situ* electric field in one voxel of the whole-body model.

Figure 3. Relative difference in 99th percentile value of *in situ* electric field in one voxel of the whole-body model.
DOSIMETRIC UNCERTAINTIES: MAGNETIC FIELD COUPLING TO PERIPHERAL NERVE

Robert Kavet*

\[ C_{GM(PN)} = 3.5 \, V \, m^{-1} \div (47.94 \, mT \times 60 \, Hz) \]
\[ = 1.217 \, V \, m^{-1} \, (T \cdot Hz)^{-1}, \quad (11) \]

\[ \sigma_{\text{Log}C_{PN}}^2 = \sigma_{\text{Log}B_{Th-PN}}^2 - \sigma_{\text{Log}E_{Th-PN}}^2, \quad (12) \]

resulting in \( GSD(C_{PN}) = 1.210 \). The probit plot derived for \( C_{PN} \) shown in Fig. 2 indicates a 99% range for \( C_{PN} \) of 0.75–1.99 V m\(^{-1}\) (T-Hz\(^{-1}\)) and a 95% range of 0.84–1.77 V m\(^{-1}\) (T-Hz\(^{-1}\)). Under the implausible scenario that \( GSD(E_{Th-PN}) = 1.0 \) (same PNS threshold in all persons), the 99% range of \( C_{PN} \) would expand to 0.67–2.22 V m\(^{-1}\) (T-Hz\(^{-1}\)). The \( C_{PN} \) range derived here under nominal assumptions are consistent with the values of \( C_{PN} \) reported in the dosimetry literature, which vary from the 42nd to 94th percentile values of the probit in Fig. 3 (data not shown).
intercomparison of in situ Electric Fields in Human Models Exposed to Spatially Uniform Magnetic Fields

KATSUAKI AGA¹, AKIMASA HIRATA⁰¹, (Fellow, IEEE), ILKKA LAASKO⁰², (Member, IEEE), HIROO TARAO³, YINLIANG DIAO⁴, (Member, IEEE), TAKAHIRO ITO⁰¹, (Member, IEEE), YOICHI SEKIBA⁵, AND KENICHI YAMAZAKI⁶, (Senior Member, IEEE)

¹Department of Electrical and Mechanical Engineering, Nagoya Institute of Technology, Nagoya 466-8555, Japan
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⁶Central Research Institute of Electric Power Industry, Yokosuka 240-0196, Japan

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This work was supported by the Ministry of Internal Affairs and Communications, Japan (KA, AH, and TI).

ABSTRACT IEEE C95.1 (radio frequency) and C95.6 (low frequency) standards for human protection from electromagnetic fields are currently under revision. In the next revision, they will be combined into one standard covering the frequency range from 0 Hz to 300 GHz. Although the C95.1 standard considers anatomical human models for deriving the relationship between internal and external field strengths, homogeneous ellipses are used in the C95.6 standard. In the guidelines of the International Commission on Non-Ionizing Radiation Protection, anatomical human models are used together with reduction factors to account for numerical uncertainty. It is worth revisiting their relationship when using different anatomical models. In this paper, five research groups performed a comparative study to update the state-of-the-art knowledge of in situ electric fields in anatomical human models when exposed to uniform low-frequency magnetic fields. The main goals were to clarify both numerical uncertainty and model variability. The computational results suggest a high consistency among in situ field strengths across laboratories; agreement in the 99th percentile with a discrepancy of under 5% was achieved. The in situ electric fields varied as expected given the models’ different dimensions. The induction factor, which is the ratio of the in situ electric fields for the temporal derivative of the external magnetic flux density, is derived for body parts and tissues. The classification of body parts into “the limb” and “other tissues” is shown to be critical for determining the in situ field strength.
TABLE 8. Ratio of the maximum magnetic field coupling for each tissue and frequency shown in Table 7 to the corresponding coupling for the ellipsoid in IEEE C95.6.

<table>
<thead>
<tr>
<th>Frequency [Hz]</th>
<th>Brain</th>
<th>Heart</th>
<th>Limbs</th>
<th>Others</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>1.80</td>
<td>0.87</td>
<td>1.16</td>
<td>1.40</td>
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<tr>
<td>759</td>
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<td>0.82</td>
<td>1.36</td>
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</tr>
<tr>
<td>1,000</td>
<td>1.72</td>
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<td>3,000</td>
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<tr>
<td>1,000,000</td>
<td>1.52</td>
<td>0.63</td>
<td>1.47</td>
<td>1.61</td>
</tr>
</tbody>
</table>

*Excludes limbs for HANAKO

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\[ = 1.217 \, \text{V m}^{-1} \, (\text{T-Hz})^{-1}, \quad (11) \]

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FIGURE 3. In situ electric field distribution: (i) NI Tech, (ii) Kagawa, (iii) CRIEPI, (iv) Aalto Univ, (v) SCAU. Models: (a) TARO, (b) HANAKO, (c) Duko.

Kavet (2015)
Current density distribution in brain (1 mm)
Current density distribution in brain (1 mm)
Current density distribution in brain (1 mm)
Current density distribution in brain (1 mm)
First application of 99th percentile (E-field exposure)

Current density averaged over 1 cm² for the models grounded as a function of height, exposure to vertical 1 kV/m 60 Hz electric field.
Summary

- Coupling coefficient for CNS (brain) in anatomical models is 80% larger than that of ellipsoid, which is attributable to the complex anatomy in the brain.

- Coupling coefficient for PNS in anatomical models is in the range of estimation by Kavet (2015); 1.5 vs 1.99 (99<sup>th</sup> percentile population estimation).

- AH comment: How to deal with some discrepancy but still well within the safety factor.
How to deal with numerical artefacts?

◆ Exposure scenarios
  Research group: Nagoya Institute of Technology
  Computational method: SPFD
  Models: Sphere (0.5, 1, 2 mm)
  7 layers: skin (80 mm of radius), fat (76 mm), muscle (74 mm), skull (72 mm), muscle (68 mm), cerebrospinal fluid (66 mm), brain (64 mm),
  Magnetic flux density : 0.1 mT (Uniform)
  Frequency : 50 Hz

◆ Post-processing: 99.0 - 99.9%ile value (intervals: 0.1%ile)
Induced E-field [mV/m]

2 mm

1 mm

0.5 mm
Voxel In-situ Electric Field value (All tissues)

Figure shows the top 1% when in-situ electric field is arranged in descending order. Even if we used smaller voxels, maximum value does not coincide with theoretical maximum value (artifact inherent to voxel model).
Figure shows the top 1% when *in-situ* electric field is arranged in descending order.
Figure shows the top 1% when *in-situ* electric field is arranged in descending order. 2-mm cube post-processing. 2-mm cube average work as a smoothing algorithms.

<table>
<thead>
<tr>
<th>Percentile [%]</th>
<th>2</th>
<th>1</th>
<th>0.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>1.58</td>
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<td>99.9</td>
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<td>99.8</td>
<td>1.41</td>
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<td>99.7</td>
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<td>99.4</td>
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</tbody>
</table>

Theoretical Maximum Value = 1.256 mV/m
Consideration of maximum induction occurring at skin-crossing hotspots

Deletion of a few percent highest field voxels in over the entire body

- Exposure scenarios
  - Research group: Nagoya Institute of Technology
  - Computational method: SPFD
  - Models: TARO(0.5, 1, 2 mm), Duke(2 mm)
  - Direction: Coronal direction (AP)
  - Magnetic flux density: 0.1 mT (Uniform)
  - Frequency: 50 Hz

- Post-processing
  - 99.0 - 99.9%ile value (intervals: 0.1%ile)
    1. ICNIRP (2010): Averaged over a 2-mm cube
    2. IEEE C95.6: Maximum value averaged over a straight line segment of 5-mm length oriented in seven directions (x, y, z and 4 slants).
# Electric field distributions (TARO)

## Surface

<table>
<thead>
<tr>
<th></th>
<th>2 mm³ Avg.</th>
<th>5 mm Avg.</th>
<th>Original</th>
</tr>
</thead>
<tbody>
<tr>
<td>TARO (2 mm)</td>
<td>TARO (1 mm)</td>
<td>TARO (0.5 mm)</td>
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</tr>
<tr>
<td>TARO (1 mm)</td>
<td>TARO (0.5 mm)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>[mV/m]</th>
<th>10</th>
<th>8</th>
<th>6</th>
<th>4</th>
<th>2</th>
<th>0</th>
</tr>
</thead>
</table>
## Electric field distributions (TARO)

### < Cross section >

<table>
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<th>2 mm³ Avg.</th>
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<tr>
<td>TARO</td>
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<td>TARO</td>
<td>TARO</td>
</tr>
<tr>
<td>(2 mm)</td>
<td>(1 mm)</td>
<td>(0.5 mm)</td>
<td>(1 mm)</td>
</tr>
</tbody>
</table>

![Electric field distributions](image)

- [0, 2, 4, 6, 8, 10] mV/m

## Notes
- The table above shows the electric field distributions for different TARO thicknesses and averaging sizes.
### Voxel in-situ electric field value

Maximum voxel value of in-situ E-Field [mV/m]

<table>
<thead>
<tr>
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  >> In TARO(1 mm), it was averaged with the electric field of 8 voxels and converted to those of 2 mm size. In TARO(0.5 mm), it was averaged with 64 voxels.
- **IEEE**: Averaged over a straight line segment of 5 mm length oriented in any direction
Top 1% when electric field is arranged in descending order

Even if different resolutions and post-processing are used, the tendencies of in-situ electric field generally agree.
It is difficult to remove the high electric field by introducing 5-mm line average.
Electric field distributions (TARO 1 mm)
| (2 mm cubic Avg.) — (5 mm Avg.) |

Post-processing: Unify voxels where are electric field is 0 V/m
The number of voxels including the air is different in the two methods.
Small item: It is necessary to consider the processing when there is an air voxel in the average space/line. As no clear difference is observed in the value, the simpler the better.
A high electric field is observed especially around the neck, crotch and armpits. >> It is well removed in 99.7%ile.

(100%ile: Electric field distribution without post-processing)
Electric field distributions (TARO 1 mm)

Distributions of E-field with 1-mm and 2-mm models are in good agreement.
Black color is the top of a percentile value when electric field is arranged in descending order. Even removing the point, the distribution does not change dramatically; adjacent voxel (just below the voxel is similar).
A high electric field in 1 mm model concentrates on the surface of the model in great number.
Electric field distributions (TARO 2 mm)

<Cross section>

100%ile  99.9%ile  99.8%ile  99.7%ile  99%ile
Electric field distributions (TARO 1 mm)

<Cross section>

100%ile  99.9%ile  99.8%ile  99.7%ile  99%ile
Distributions of high electric field (TARO 2 mm)

<Cross section>

0%  0.1%  0.2%  0.3%  1%
Distributions of high electric field (TARO 1 mm)

<Cross section>

0% 0.1% 0.2% 0.3% 1%
Distributions of high electric field (Duke 2 mm)
Distributions of high electric field (Duke 2 mm)

<Surface>

0%  0.1%  0.2%  0.3%  1%
Electric field distributions (Duke 2 mm)

<Cross section>

100%ile  99.9%ile  99.8%ile  99.7%ile  99%ile
Distributions of high electric field (DUKE 2 mm)

<Cross section>

0%  0.1%  0.2%  0.3%  1%
Effect of model resolution and percentile value

E-field becomes only at the surface voxel. When 2-mm resolution model is used, the skin is excluded. If higher-resolution model is used, 99.xx th percentile would be reasonable solution. The uncertainty observed in the results is within the range of the uncertainty.

IEEE C95.1 (2019): Definition of safety factor

- safety factor (SF): A divisor (≥ 1) applied to the exposure level that causes an adverse effect, used to establish a dosimetric reference limit (DRL) that includes inter-subject biological variability, uncertainties concerning threshold effects due to pathological conditions or drug treatment, uncertainties in computational models, uncertainties in dosimetry, and variations in temperature and humidity
On the Issues of LF Numerical Dosimetry

Prof. Valerio De Santis

Department of Industrial and Information Engineering and Economics
University of L’Aquila, 67100 L'Aquila, Italy

valerio.desantis@univaq.it
v.desantis@ieee.org
Outline

• Introduction
  - LF numerical dosimetry review

• LF dosimetry issues
  - anatomical issues (skin modeling, segmentation,…)
  - dielectric properties issues (anisotropy,…)
  - solver convergence issues (staircasing, singularities,…)

• Compliance issues
  - ICNIRP issues
  - IEEE-ICES issues
  - post-processing issues (99.0 vs 99.9%ile, volume vs line averaging)

• Conclusions and proposed actions
Introduction

- Are simplified ellipsoidal uniform conductivity (EUC) models accurate for LF dosimetry or detailed anatomical (DA) models are needed?

\[ E = \omega B \frac{a^4 u^2 + b^4 v^2}{a^2 + b^2} \]

IEEE C95.6  IEC TC-106 WG9  DA models for science
Introduction

• How to address the skin for DA models?

<table>
<thead>
<tr>
<th>Exposed tissue</th>
<th>Frequency $f_e$ (Hz)</th>
<th>Persons in unrestricted environments $E_0$ (V/m)</th>
<th>Persons permitted in restricted environments $E_0$ (V/m)</th>
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</thead>
<tbody>
<tr>
<td>Brain $^b$</td>
<td>20</td>
<td>5.89 x 10^{-3}</td>
<td>1.77 x 10^{-2}</td>
</tr>
<tr>
<td>Heart</td>
<td>167</td>
<td>0.943</td>
<td>0.943</td>
</tr>
<tr>
<td>Limb</td>
<td>3350</td>
<td>2.10</td>
<td>2.10</td>
</tr>
<tr>
<td>Other tissues</td>
<td>3350</td>
<td>0.701</td>
<td>2.10</td>
</tr>
</tbody>
</table>

NOTE—Tabulated values are given as rms quantities.

---

$a$ Interpretation of Table 1 is as follows: $E_i = E_0$ for $f \leq f_e$; $E_i = E_0 \left( f / f_e \right)$ for $f \geq f_e$.

$b$ The in situ magnetic field dosimetric reference limit (DRL) below 10 Hz shall be restricted to a peak value of 167 mT for the unrestricted environment and a peak value of 500 mT for restricted environments. In situ magnetic field DRLs for frequencies above 10 Hz are not necessary because Table 2 (see 4.2.2.1) electrostimulation criteria dominate the biological effect.

$c$ Parameters $E_0$ (induced in situ electric field in V/m) and $f_e$ (in Hz) as expressed in Equation (1) apply to DRLs in various regions of the body.

$d$ DRLs in Table 1 do not apply to induced fields or current crossing skin-to-skin contact (see B.2.1.2.2.2).
LF Numerical Dosimetry Review

- Gandhi et al. (1984, 1988, 1992)
  - IM, FDTD with Frequency Scaling (10 MHz)

  - SPFD, QS-FDTD, hybrid QS-FDTD/SPFD

  - IM and SPFD (SPFD preferred)

  - IM, SPFD, QS-FDTD, FM-SCM (Japan InterLab study)

- Scorretti et al. (2004, 2010)
  - FEM M-QS Solver (conformal mesh)

- Laakso et al. (2012), De Santis et al. (2014)
  - SPFE, FEM (voxelized grid)
Outline

• Introduction
  - LF numerical dosimetry review

• LF dosimetry issues
  - anatomical issues (skin modeling, segmentation,…)
  - dielectric properties issues (anisotropy,…)
  - solver convergence issues (staircasing, singularities,…)

• Compliance issues
  - ICNIRP issues
  - IEEE-ICES issues
  - post-processing issues (99.0 vs 99.9%ile, volume vs line averaging)

• Conclusions and proposed actions
Anatomical Model Artifacts

segmentation issues

skin issues

armpits

contact

groin
Skin Modeling (Geometrical Issues)

Figure 2. Anatomy of thin skin. Abbreviations are explained in the text (KRISTIC 1991) - (AM) arrector pilis muscles, (AS) apocrine glands, (AT) adipose tissue, (D) dermis, (DP) dermal papillae, (E) epidermis, (Ed) eccretery duct, (ER) epithelial ridges, (ES) eccretery glands, (HB) hair bulbs, (HF) hair follicles, (Hy) hypodermis, (IM) Meissner’s tactile corpuscles, (NF) nerve fascicles, (PL) papillary layer, (RL) reticular layer, (SG) sebaceous glands, (V-P) Vater-Pacini corpuscles.

Figure 3. Anatomy of thick skin. Abbreviations are explained in the text (KRISTIC 1991) - (A) artecles, (AT) adipose tissue, (C) concavities, (CL) capillary loops, (D) dermis, (DP) dermal papillae, (E) epidermis, (Ed) eccretery ducts of sweat glands, (Ed) eccretery duct, (Ed) eccretery ducts, (ER) eccretery ducts, (ER) eccretery ducts, (ER) eccretery ducts, (ER) eccretery ducts, (ER) eccretery ducts, (F) furunculus, (G) furunculus, (Hy) hypodermis, (NF) nerve fascicles, (PL) papillary (RC) reticulum, (RL) reticular layer, (RS) nerve autoglandular, (SC) stratum corneum, stratum granulosum, (V) veins, (V-P) Vater-Pacini corpuscles.
Skin Modeling (Geometrical Issues)

- What conductivity should be assigned to the single skin layer?

Dielectric Properties Issues

- Increased measurement uncertainty at LF [1]-[2]
  - ± 5-15% at RF (above 1 MHz)
  - ± 15-25% at LF (below 1 MHz)
  - Uncertainty up to several order of magnitudes for the relative permittivity

- Big uncertainty on the skin dielectric properties [3]-[5]
  - Practical issues (electrode shape/configuration, moisture of the skin, …)
  - Large variation of tissue composition among the several skin layers
  - Huge variation in conductivity values (Gabriel 0.0002 S/m vs Dimbylow 0.1 S/m)

Anisotropy of Skeletal Muscle

\[ J = \mathbf{s} \cdot \mathbf{E} \quad \mathbf{s} = \begin{pmatrix} \sigma_x & 0 & 0 \\ 0 & \sigma_y & 0 \\ 0 & 0 & \sigma_z \end{pmatrix} \]

- \( \sigma_x = \sigma_y = \sigma_z = \sigma_0 \) (Set I) isotropic
- \( \mathbf{s} = \begin{pmatrix} \sigma_1 & 0 & 0 \\ 0 & \sigma_1 & 0 \\ 0 & 0 & \sigma_1 \end{pmatrix} \) (Sets A, B) anisotropic (vertical)
- \( \mathbf{s} = \begin{pmatrix} \sigma_1 & 0 & 0 \\ 0 & \sigma_1 & 0 \\ 0 & 0 & \sigma_1 \end{pmatrix} \) (Sets C, D) anisotropic (orizzontal)

| Table 1. Conductivity values (in S m⁻¹) used in the various runs. |
|---|---|---|---|---|---|
| Run | I | A | B | C | D |
| \( \sigma_{x,y} \) | 0.35 | 0.20 | 0.20 | 0.35 | 0.70 |
| \( \sigma_z \) | 0.35 | 0.35 | 0.70 | 0.20 | 0.20 |

Anisotropy of Muscle and Nerve

LF Solver Issues: SEMCAD/Sim4Life

- Scalar Potential Finite Element (SPFE) method
- similar to FEM → **convergency** issues
- voxel gridding → **staircasing** issues
- flexible and user-friendly for sources and HBMs
- non-uniform magnetic sources

**QS approximation**

\[ \nabla \times \frac{1}{\mu} \nabla \times \mathbf{A} = \mathbf{j}_0 \]

**μ ≡ \mu_0:** 

\[ \mathbf{A}_0 (\mathbf{r}) = \frac{\mu_0}{4\pi} \int_{\Omega} \mathbf{j}_0 (\mathbf{r}') \frac{d\mathbf{r}'}{|\mathbf{r} - \mathbf{r}'|} \]

**Charge continuity**

\[ \nabla \cdot \varepsilon \nabla \phi = j \omega \nabla \cdot (\varepsilon \mathbf{A}_0) \]

**Conductive dominated issue**

\[ \sigma \ll \omega \varepsilon: \quad \nabla \cdot (\varepsilon \nabla \phi) = j \omega \nabla \cdot (\varepsilon \mathbf{A}_0) \]

**Induced fields**

\[ \mathbf{E} = -j \omega \mathbf{A} - \nabla \phi \]

**frequency Scaling**

\[ \mathbf{J} = \sigma \mathbf{E} \]
TEAM benchmark*: Problem 6 (hollow sphere)  

\[ \mathbf{B} = B_z \mathbf{z} \]

\[ E = \frac{j \omega B_z z}{2} \]

*The TEAM Benchmarks originate from the Argonne National Laboratory (ANL) in 1985 where a series of workshops started in 1986. In short, the goal of the workshops and ensuing benchmarks was to "show the effectiveness of numerical techniques and associated computer codes in solving electromagnetic field problems."

Larry R. Turner, "The TEAM Workshops: A Short History" LS Note 153, Argonne National Laboratory,  
Convergency Issues

- Gandhi vs Stuchly (InterLab Study 2000)
  - IM (Gandhi) vs SPFD (Stuchly)
  - Up to 200% differences (different CEM, HBM, Resolution, Conductivities)

- Hirata et al. (Japan InterLab Study 2010)
  - IM, SPFD, QS-FDTD, FM-SCM (fixed TARO HBM, fixed conductivities)
  - Up to 40% error between the same method
  - Up to 45% error between the several methods
  - Up to 10% error for induced J in the CNS (except one group)

- Aga et al. (SC6-WG2 InterLab Study 2018)
  - FEM vs SPFD (fixed CEM, HBM, Resolution, Conductivities)
  - Up to 5% differences (different CEMs) with peak of 16% (HANAKO HBM)
Staircasing Issues

- EPRI TR-111678
  - Overestimation of $J$ due to constricted current flow around inside corners (artificially created by the staircasing)

- Stuchly-Okoniewski (QS-FDTD 2000)
  - Overestimation of $E$, noticed principally at locations where there is a large discontinuity in material properties (air-tissue interface)
  - In the FDTD, it is particularly noticeable for the electric field, as the electric field components are always located on voxel edges, where the object material properties change


Staircasing Issues

Uniform time-varying magnetic fields (sphere)

$E = \frac{j \omega B_z r}{2}$

$a = 0.08 \text{ m}$

$f = 50 \text{ Hz}$
Staircasing Issues

Uniform time-varying magnetic field (ellipsoid)

\[ B(r) = B_0 z, \]

\[ A(r) = \frac{1}{2} B_0 r \sin \theta \phi \]

\[ J(r, \theta) = \frac{2 \pi \sigma \mu H}{1 + \beta^2} \frac{r}{\sqrt{\sin^2 \theta + \beta^2 \cos^2 \theta}} \]

IEEE C95.3.1, IEEE Recommended Practice for Measurements and Computations of Electric, Magnetic, and Electromagnetic Fields with Respect to Human Exposure to Such Fields, 0 Hz to 100 kHz, 2010.
Staircasing Issues

Uniform time-varying magnetic field (double-layer sphere)

\[ B(r) = B_0 \hat{z}, \]

\[ A(r) = \frac{1}{2} B_0 r \sin \theta \phi \]

Analytic solution in [2]


Staircasing Issues

Uniform time-varying magnetic field gradients (sphere)

\[ A = -\frac{1}{2} G_z y z x + \frac{1}{2} G_z x z y \]

\[ B = -\frac{1}{2} G_z x x - \frac{1}{2} G_z y y + G_z z z \]

\[ E_\phi = -\frac{1}{4} j \omega G_z r^2 \sin(2\theta) \]

Numerical Results (Analytic vs Numerical)

Analytic

Analytic solution*

\[ E_\phi = -\frac{1}{4} j \omega G_z r^2 \sin(2\theta) \]

Numerical

\( a = 0.08 \text{ m} \)
\( f = 1 \text{ kHz} \)
\( G_z = 30 \text{ mT/m} \)

### Numerical Results (Sensitivity Analyses)

#### Effect of the mesh resolution

<table>
<thead>
<tr>
<th>$a$ [m]</th>
<th>$f$ [Hz]</th>
<th>Tollerance</th>
<th>N. of Cells</th>
<th>$\varepsilon$ %</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.08</td>
<td>1e3</td>
<td>1e-8</td>
<td>2653</td>
<td>3.160</td>
</tr>
<tr>
<td>0.08</td>
<td>1e3</td>
<td>1e-8</td>
<td>9653</td>
<td>1.698</td>
</tr>
<tr>
<td>0.08</td>
<td>1e3</td>
<td>1e-8</td>
<td>279380</td>
<td>0.584</td>
</tr>
<tr>
<td>0.08</td>
<td>1e3</td>
<td>1e-8</td>
<td>2173376</td>
<td>0.324</td>
</tr>
</tbody>
</table>

#### Effect of the relative tollerance

<table>
<thead>
<tr>
<th>$a$ [m]</th>
<th>$f$ [Hz]</th>
<th>Tollerance</th>
<th>N. of Cells</th>
<th>$\varepsilon$ %</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.08</td>
<td>1e3</td>
<td>1e-2</td>
<td>9653</td>
<td>1.695</td>
</tr>
<tr>
<td>0.08</td>
<td>1e3</td>
<td>1e-4</td>
<td>9653</td>
<td>1.693</td>
</tr>
<tr>
<td>0.08</td>
<td>1e3</td>
<td>1e-6</td>
<td>9653</td>
<td>1.696</td>
</tr>
<tr>
<td>0.08</td>
<td>1e3</td>
<td>1e-8</td>
<td>9653</td>
<td>1.698</td>
</tr>
</tbody>
</table>

#### Effect of the frequency

<table>
<thead>
<tr>
<th>$a$ [m]</th>
<th>$f$ [Hz]</th>
<th>Tollerance</th>
<th>N. of Cells</th>
<th>$\varepsilon$ %</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.08</td>
<td>10</td>
<td>1e-8</td>
<td>9653</td>
<td>1.701</td>
</tr>
<tr>
<td>0.08</td>
<td>50</td>
<td>1e-8</td>
<td>9653</td>
<td>1.698</td>
</tr>
<tr>
<td>0.08</td>
<td>100</td>
<td>1e-8</td>
<td>9653</td>
<td>1.695</td>
</tr>
<tr>
<td>0.08</td>
<td>1e3</td>
<td>1e-8</td>
<td>9653</td>
<td>1.693</td>
</tr>
<tr>
<td>0.08</td>
<td>1e4</td>
<td>1e-8</td>
<td>9653</td>
<td>1.696</td>
</tr>
<tr>
<td>0.08</td>
<td>1e5</td>
<td>1e-8</td>
<td>9653</td>
<td>1.688</td>
</tr>
</tbody>
</table>

#### Effect of the radius

<table>
<thead>
<tr>
<th>$a$ [m]</th>
<th>$f$ [Hz]</th>
<th>Tollerance</th>
<th>N. of Cells</th>
<th>$\varepsilon$ %</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.04</td>
<td>1e3</td>
<td>1e-8</td>
<td>1579</td>
<td>5.184</td>
</tr>
<tr>
<td>0.06</td>
<td>1e3</td>
<td>1e-8</td>
<td>4446</td>
<td>3.578</td>
</tr>
<tr>
<td>0.08</td>
<td>1e3</td>
<td>1e-8</td>
<td>9653</td>
<td>1.698</td>
</tr>
<tr>
<td>0.10</td>
<td>1e3</td>
<td>1e-8</td>
<td>19214</td>
<td>2.068</td>
</tr>
<tr>
<td>0.12</td>
<td>1e3</td>
<td>1e-8</td>
<td>31706</td>
<td>1.684</td>
</tr>
<tr>
<td>0.16</td>
<td>1e3</td>
<td>1e-8</td>
<td>70168</td>
<td>1.307</td>
</tr>
</tbody>
</table>
Numerical Results (Analytic vs Numerical)

- 2653 Cells
  - Percentage error (%)
- 279380 Cells
  - Percentage error (%)
- 9653 Cells
  - Percentage error (%)
- 2173376 Cells
  - Percentage error (%)

\[ a = 0.08 \text{ m} \]
\[ f = 1 \text{ kHz} \]
\[ G_z = 30 \text{ mT/m} \]

\[ E_\phi = -\frac{1}{4} j \omega G_z r^2 \sin(2\theta) \]
Singularity Issues

Singularity Issues

Singularity Issues

conformal mesh

grid1 (1 mm)

6.17 e-5

rectilinear grid

grid2 (0.5 mm)

7.66 e-5

grid3 (0.25 mm)

9.61 e-5
Singularity Issues

Table 2. Maximum induced electric field (V/m) for different numerical methods and compliance procedures

<table>
<thead>
<tr>
<th>averaging procedure</th>
<th>conformal</th>
<th>rectilinear grid1</th>
<th>rectilinear grid2</th>
<th>rectilinear grid3</th>
</tr>
</thead>
<tbody>
<tr>
<td>unaveraged</td>
<td>$4 \times 10^{-5}$</td>
<td>$6.17 \times 10^{-5}$</td>
<td>$7.88 \times 10^{-5}$</td>
<td>$9.61 \times 10^{-5}$</td>
</tr>
<tr>
<td>2 x 2 x 2 mm³ average</td>
<td>–</td>
<td>$4.01 \times 10^{-5}$</td>
<td>$4.21 \times 10^{-5}$</td>
<td>$4.31 \times 10^{-5}$</td>
</tr>
<tr>
<td>99th percentile</td>
<td>–</td>
<td>$1.78 \times 10^{-5}$</td>
<td>$1.78 \times 10^{-5}$</td>
<td>$1.79 \times 10^{-5}$</td>
</tr>
</tbody>
</table>

99th percentile can lead to notable underestimations
Outline

• Introduction
  - LF numerical dosimetry review

• LF dosimetry issues
  - anatomical issues (skin modeling, segmentation,…)
  - dielectric properties issues (anisotropy,…)
  - solver convergence issues (staircasing, singularities,…)

• Compliance issues
  - ICNIRP issues
  - IEEE-ICES issues
  - post-processing issues (99.0 vs 99.9%ile, volume vs line averaging)

• Conclusions and proposed actions
Quandaries of ICNIRP 2010

- ICNIRP 2010 basic restrictions

Induced electric field must be averaged. As a practical compromise, satisfying requirements for a sound biological basis and computational constraints, ICNIRP recommends determining the induced electric field as a vector average of the electric field in a small contiguous tissue volume of $2 \times 2 \times 2 \text{ mm}^3$. For a specific tissue, the 99th percentile value of the electric field is the relevant value to be compared with the basic restriction.

- Implemented solution in SEMCAD/Sim4Life

$$\langle E(r_0) \rangle_V = \frac{1}{V} \sum_n E(r_n) f_n V_n$$

where $r_0$ is the location of the voxel center, $V$ is fixed at 8 mm$^3$, $V_n$ is the volume of the $n^{th}$ voxel within the cube and $0 < f_n \leq 1$ is the filling factor.
Quandaries of IEEE C95.6-2002

• IEEE C95.6 basic restrictions

\[ E_i = E_0 \quad \text{for } f \leq f_e \]  \hspace{1cm} (1a)

\[ E_i = E_0 \frac{f}{f_e} \quad \text{for } f \geq f_e \]  \hspace{1cm} (1b)

where \( E_i \) is the maximum permissible induced *in situ* electric field. The basic restrictions on the *in situ* electric field apply to an arithmetic average determined over a straight line segment of 0.5 cm length oriented in any direction within the tissue identified in Table 1.

• Implemented solution in SEMCAD/Sim4Life

\[
\langle E(r_0) \rangle_L = \frac{\hat{l}_0}{L} \int_L E(r) \cdot \hat{l}_0 \ dl = \frac{K}{L} \hat{l}_0
\]

\[ \hat{l}_0 = \frac{E(r_0)}{|E(r_0)|} \]

where \( L \) is fixed at 5 mm, \( K \) is the integral of E-fields along the line segment. For the averaging line segment to be entirely within the tissue, no averaging will be performed at a voxel if the 5 mm line segment extends out of the tissue of interest.
Selection of 99th Percentile

full-weighting  

Table 3. Maximal induced electric field

<table>
<thead>
<tr>
<th></th>
<th>$E_{av}$ (V/m)</th>
<th>$E_{99^{th}, full}$ (V/m)</th>
<th>$E_{99^{th}, ts_1}$ (V/m)</th>
<th>$E_{99^{th}, ts_2}$ (V/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full-weighting</td>
<td>0.192</td>
<td>0.0013</td>
<td>0.0021</td>
<td>0.0037</td>
</tr>
</tbody>
</table>

up to 3-fold variations

IEEE ICES

SC6 Meeting, 25 January 2019, Plantation Florida, USA
Summary of Compliance Issues

• 99th percentile should not be recommended as a general guideline for post-processing (prone to underestimations)

• 8 mm³ volume averaging good only for very fine grid resolutions but **not for inhomogeneous models** (see Gomez TEMC 2018)

• 5 mm line averaging in **any direction is very cumbersome**

• both ICNIRP and IEEE do not specify the averaging strategy – contiguous vs non-contiguous way?

  • propose a “dynamic” solution to the problem?

  • Uncertainty budget for all numerical artifacts
Proposed Solutions: post-processing

adaptive relative range

\[ \text{Detection Point} = \mu + 2.44 \times \text{IQR} \]

- 99.0 vs 99.9 percentile compared
- proposed “detection point” based on statistic analyses

Proposed Solutions

adaptive relative range

\[ \Delta = \frac{\max(E_{\text{grid}}) - \min(E_{\text{grid}})}{\text{avg}(E_{\text{grid}})} \]
# Uncertainty Budget

## Table 6: Numerical uncertainty for the evaluation of the induced PNS electric field

<table>
<thead>
<tr>
<th>Uncertainty Source</th>
<th>Tolerance $a_i$ (dB)</th>
<th>Distrib.</th>
<th>$d_i$</th>
<th>$c_i$</th>
<th>Std. Unc. $u_i$ (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source modeling</td>
<td>1.44</td>
<td>normal</td>
<td>1</td>
<td>1</td>
<td>1.44</td>
</tr>
<tr>
<td>Conductive dominated approx</td>
<td>0.17</td>
<td>normal</td>
<td>1</td>
<td>1</td>
<td>0.17</td>
</tr>
<tr>
<td>Grid resolution</td>
<td>0.03</td>
<td>normal</td>
<td>1</td>
<td>1</td>
<td>0.03</td>
</tr>
<tr>
<td><strong>Tissue parameters</strong></td>
<td><strong>0.96</strong></td>
<td>normal</td>
<td>1</td>
<td>1</td>
<td><strong>0.96</strong></td>
</tr>
<tr>
<td>E-field averaging</td>
<td>1.21</td>
<td>normal</td>
<td>1</td>
<td>1</td>
<td>1.21</td>
</tr>
<tr>
<td>Frequency scaling</td>
<td>0.26</td>
<td>normal</td>
<td>1</td>
<td>1</td>
<td>0.26</td>
</tr>
<tr>
<td>Combined std. uncertainty $u_c$</td>
<td></td>
<td>RSS</td>
<td></td>
<td></td>
<td>2.04</td>
</tr>
<tr>
<td><strong>Expanded uncertainty $U$ ($k = 2$)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>3.69</strong></td>
</tr>
</tbody>
</table>

## Table 7: Numerical uncertainty for the evaluation of the induced CNS electric field

<table>
<thead>
<tr>
<th>Uncertainty Source</th>
<th>Tolerance $a_i$ (dB)</th>
<th>Distrib.</th>
<th>$d_i$</th>
<th>$c_i$</th>
<th>Std. Unc. $u_i$ (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source modeling</td>
<td>1.44</td>
<td>normal</td>
<td>1</td>
<td>1</td>
<td>1.44</td>
</tr>
<tr>
<td>Conductive dominated approx</td>
<td>0.17</td>
<td>normal</td>
<td>1</td>
<td>1</td>
<td>0.17</td>
</tr>
<tr>
<td>Grid resolution</td>
<td>0.10</td>
<td>normal</td>
<td>1</td>
<td>1</td>
<td>0.10</td>
</tr>
<tr>
<td><strong>Tissue parameters</strong></td>
<td><strong>0.79</strong></td>
<td>normal</td>
<td>1</td>
<td>1</td>
<td><strong>0.79</strong></td>
</tr>
<tr>
<td>E-field averaging</td>
<td>0.83</td>
<td>normal</td>
<td>1</td>
<td>1</td>
<td>0.83</td>
</tr>
<tr>
<td>Frequency scaling</td>
<td>0.26</td>
<td>normal</td>
<td>1</td>
<td>1</td>
<td>0.26</td>
</tr>
<tr>
<td>Combined std. uncertainty $u_c$</td>
<td></td>
<td>RSS</td>
<td></td>
<td></td>
<td>1.8</td>
</tr>
<tr>
<td><strong>Expanded uncertainty $U$ ($k = 2$)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>3.29</strong></td>
</tr>
</tbody>
</table>

Outline

• Introduction
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  - solver convergence issues (staircasing, singularities,…)

• Compliance issues
  - ICNIRP issues
  - IEEE-ICES issues
  - post-processing issues (99.0 vs 99.9%ile, volume vs line averaging)

• Conclusions and proposed actions
How to Derive Canonical Models?

- Are simplified (e.g. homogeneous ellipsoid) models accurate for LF dosimetry or detailed anatomical (DA) models are needed?

\[ E = \omega B \sqrt{\frac{a^4u^2 + b^4v^2}{a^2 + b^2}} \]
Canonical Models for the Estimation of $E_{\text{CNS}}$

- **basic mechanisms for $E_{\text{CNS}}$ exposure**
  - Faraday’s Law of induction
    - larger brain $\rightarrow$ higher $E_{\text{CNS}}$
  - shape of the brain
    - sharp folding $\rightarrow$ higher $E_{\text{CNS}}$
  - CSF and grey matter conductivities
    - higher $\sigma$-contrast $\rightarrow$ higher $E_{\text{CNS}}$
  - dimension of CSF-brain-CSF slab
    - thinner brain slab $\rightarrow$ higher $E_{\text{CNS}}$

- **larger $\sigma$-contrast**
  - $\sigma_{\text{CSF}} = 2 \text{ S/m}$
  - $\sigma_{\text{brain}} = 0.075 \text{ S/m}$

Proposed Canonical Models

Proposed Canonical Models

Proposed Canonical Models

- variations of the canonical model parameters
  - sphere diameter as the largest brain of 95% population (D = 20 cm)
  - thickness of the brain slab (t = 1 cm as good trade-off)
  - largest $\sigma$-contrast ($\sigma_{\text{CSF}} = 2 \, \text{S/m}$ and $\sigma_{\text{brain}} = 0.075 \, \text{S/m}$)

Validation with Anatomical Models

Virtual Population, IT’IS Foundation, Zurich, CH. [www.itis.ethz.ch/virtualpopulation]
Validation with Anatomical Models

- LAT exposure always conservative except for Glenn
- orientation is irrelevant for the considered probe design
- probe v2 as the best canonical model
Canonical Models for the Estimation of $E_{PNS}$

- **basic mechanisms for $E_{PNS}$ exposure**
  - Faraday’s Law of induction
    - larger body $\rightarrow$ higher $E_{PNS}$
  - shape of the body
    - sharp folding $\rightarrow$ higher $E_{PNS}$
  - skin and SAT conductivities
    - higher $\sigma$-contrast $\rightarrow$ higher $E_{PNS}$
  - dimension of SAT-skin-SAT slab
    - thinner skin slab $\rightarrow$ higher $E_{PNS}$

- **larger $\sigma$-contrast**
  - $\sigma_{\text{muscle}} = 0.23 \text{ S/m}$
  - $\sigma_{\text{skin}} = 0.0002 \text{ S/m}$

Proposed Canonical Models

- variations of the canonical model parameters
  - ellipsoid dimensions as the 95% largest body (H = 1 m, W = 60 cm, D = 35 cm)
  - thickness of the skin slab (t = 1 cm as good trade-off)
  - larger σ-contrast (σ_{body} = 0.23 S/m and σ_{skin} = 0.0002 S/m)

Validation with Anatomical Models

- AP exposure always conservative
- orientation is now relevant for the considered probe design
- probe v5 over- v4 under-conservative (scaling is needed)
Considerations on the Estimation of $E_{\text{PNS}}$

- 2 probe designs have been proposed for non-touching postures
  - probe v5 is overly conservative
  - probe v4 is not conservative (scaling is needed)

- alternative phantoms must be investigated for touching postures

Schmid et al.
On the importance of body posture and skin modelling with respect to in situ electric field strengths in magnetic field exposure scenarios.

De Santis et al.
An equivalent skin conductivity model for low-frequency magnetic field dosimetry.

De Santis et al.
A novel homogenization procedure to model the skin layers in LF numerical dosimetry.
Conclusions and Future Works

• **LF numerical** dosimetry suffer from many **issues**
  - anatomy, diel. prop., solver convergence (skin as most influent)
  - improve HBMs, tissue meas, CEMs, (conformal techniques welcomed)

• **Compliance issues** with both exposure limits (ICNIRP and IEEE)
  - 99th percentile (ICNIRP) should be removed
  - fixed strategies (99.0 vs 99.9%ile, 8 mm$^3$ vs 5 mm) are **ill-posed**
  - a “dynamic” solution should be find

• **Canonical models** have been proposed
  - good accuracy for CNS exposure
  - poor accuracy for PNS exposure
  - postures should be taken into account
Questions?

Thank you for your attention!