Minutes
IEEE/ICES TC95 Subcommittee 6 EMF Dosimetry Modeling

0900 – 1130 h (EDT)
Monday, 18 May 2020
Internet Meeting

1. Call to Order
Chairman called the meeting to order at 0903 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 Ziskin that was seconded by Cory, the agenda was approved as presented (see Attachment 2).

4. Approval of the Minutes (January 2018 Meeting)
Following a motion by Bailey that was seconded by Graff, the minutes of the 23 January 2020 meeting have been approved. It includes call for patent and is mentioned at the bottom of the agenda.

5. Chairman’s Report
Hirata began the Chairman’s report on the ICNIRIP Data Gap document. Also, he reported that the revision of LF guidelines was included in the next 4-year projects of ICNIRP. For RF exposures, the reference level for local exposure has been newly introduced in IEEE C95.1-2019 and ICNIRP. Inconsistencies between ICNIRP and IEEE are mentioned. Also, suggested projects with potential participants are listed. Tell asked about activities concerning the consistency between contact current limits and induced electric field in ICNIRP. Hirata mentioned that ICNIRP had not yet discussed this issue.

6. Working Group Reports
WG1 Report
Co-Chair Alex Legros announced the activities and purpose of the next SC3 meeting. As Legros has been appointed as SC3 chair, some activity may be moved to SC3. No additional report on the activities of WG1 at the moment.

WG4: Exploring the Electrostimulation Threshold in Brain (See Attachment 3)
Co-Chair, Jose Gomez-Tames, reported recent activities, including extended intercomparison considering different model conditions for axonal neural stimulation (> 300 Hz). Also, the importance of variability in the stimulation thresholds was reported. These variabilities will be considered to analyze further conservative of the current limits. Patrick commented on the relevance of the activities of the WG. He mentioned that synaptic interactions are important and need further exploration that can be considered as future work. Esra commented on the need to investigate not only axonal stimulation but also subthreshold effects for dosimetry evaluation.

WG5: Definition of Incident Power Density (See Attachment 4)
Walid El Hajj (chair) gave a presentation discussing candidates for IPD definition. A simulation was conducted using different modelling scenarios in which several groups participated to compare the two IPD definitions. Correlation with temperature elevations and standard deviation of heating were used to explore the two definitions. Other techniques were used as well (e.g., thermographic measurements). The
draft PAR (P2889) was submitted and will be considered at the 6/2/20 IEEE SA Standards Board Meeting, and several papers are under preparation. Saloric asked the information about the phantom.

7. Technical Presentations

SAR evaluation in learning-based smoothed head models (See Attachment 5)
Co-chair of TF2, Rashed presented technical research results that demonstrate the use of machine learning approach (deep learning) in the automatic estimation of dielectric properties in human head models. A deep architecture consists of several convolutional neural networks (CNN) layers were used to estimate conductivity, relative permittivity, and tissues density from T1/T2 MRI scans. The study used ten subjects for training and eight for testing. Then, specific absorption rate (SAR) values were presented for a dipole antenna scenario considering the standard and learning-based approaches. Results of both standard and learning-based methods were of high consistency, while SAR maps were presented in more smooth patterns. It is also noted that segmentation of the head tissues was not required when learning-based head models are generated, which can significantly reduce the computation cost required for segmentation. Valerio asked about the image resolutions (1 mm).

Inter-individual variations in induced E-field at ELF (See Attachment 6)
Laakso presented the computational dosimetry data for uniform magnetic field exposure. More than 100 head models were used to derive the age dependence of induced electric field. The data by Dimbylow, which is used in the reference of ICNIRP guidelines 2010, is very high (outlier) due to the discontinuity of the CSF layer. The induced electric field in the ellipse is smaller than that in the head model due to the model inhomogeneity. Reilly comment on the advance anatomical models has improved when comparing to the past models, so the elliptical model was adopted at that time. Also, recalculation of the limits using new phosphenes thresholds is recommended.

Non-uniform exposure to pulsed LF fields (See Attachment 7)
Giaconne discussed numerical artifacts that appear in voxelized models, such as staircasing, and summarized metrics treating the artifacts in IEEE and ICNIRP and recent statistical or adaptive metrics. A comparison of the different metrics for a case study (welding gun) was conducted. For local exposure, in particular, further consideration of the metrics is recommended. Diao commented on the line averaging metric implementation in which many line orientations is necessary for finding the maximum electric field.

Partial body exposure from LF field (See Attachment 8)
Miwa discussed the relationship between the external magnetic field and the internal electric field for uniform exposure. The motivation is the gap between canonical ellipse (C95.6-2002) and detailed models. He demonstrated relationships of the internal quantities with the model dimensions. A formula is proposed that permits the estimation of the internal electric field in different canonical shapes. Next, studies need to consider the reason why the human model is different from the phenomenon of cuboid and ellipses.

8. New Business
Discussion of how SC6 can contribute with SC3/4. Kavet commented on dosimetry comparison for near and far field.

9. Time and Place of Next Meeting
The next SC6 meeting will be held in January 2021. Due to the crisis of COVID-19, exact information will be announced later.

10. Adjourn
There being no further business, the meeting was adjourned at 11:40 h.
### Attendance List

**TC95 SC6 (EMF Modeling and Dosimetry): 18 May 2020, 0900-1130 h**

<table>
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<tr>
<th>Last Name</th>
<th>First Name</th>
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<td>De Santis</td>
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ATTACHMENT 2

Approved Agenda

IEEE/ICES TC95 Subcommittee 6 EMF Dosimetry Modeling

0900 – 1130 h (EDT)
18 May 2020

Internet Meeting

1. Call to Order
2. Introduction of those Present
3. Approval of Agenda
4. Approval of the Minutes (January 2020 Meeting)
5. Call for Patents
6. Chairman’s Reports
7. Working Group Reports
   - WG1: Uncertainties Related to Electrostimulation Threshold
     Legros/Laakso
   - WG4: Exploring the Electrostimulation Threshold in Brain
     Joseph/Gomez
   - WG5: Definition of Incident Power Density
     El Hajj
8. Technical Presentations
   - SAR evaluation in learning-based smoothed head models
     Rashed
   - Inter-individual variations in induced E-field at ELF
     Laakso
   - Non-uniform exposure to pulsed LF fields
     Giaccone
   - Partial body exposure from LF field
     Miwa
9. New Business
10. Time and Place of Next Meeting

Participants have a duty to inform the IEEE of holders of essential patent claims if they or their affiliations hold such claims. Check the web link on the agenda for more details. If anyone in this meeting is personally aware of any patent claims that are potentially essential to implementation of the proposed standard(s) under consideration by this group and that are not already the subject of an Accepted Letter of Assurance, please speak to the committee chair today.
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: 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

Within the general scope, WG4 considers unresolved issues raised in the 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)*

   - Statistical distribution
WG4: Thresholds in CNS

1. Consistency of the excitation neurons for different scenarios.

Two Steps:

Induction Model

Electrostimulation model (ES)

- Consistency of the E-field computation
- Consistency of the neuron models
- Comparison of different neuronal models
1. CNS thresholds: Intercomparison (Previous study)

- **Aim:** Intercomparison of TMS-induced EF activation for fast-conducting thickly myelinated pyramidal fibers for corticospinal tracts
- **Induction model (E-field):** SPFD and FEM
- **Electrode stimulation model:** Spatially extended nonlinear nodal (SENN†) model
  - The ionic membrane currents formulated using CRRSS model
1. CNS thresholds: Intercomparison (Previous study)

- Allowable external magnetic field strength and internal electric field established in both guidelines/standards derived from PNS are at least 10 times lower than the one needed for the stimulation of the CNS.
1. CNS thresholds: Intercomparison (Previous study)

Limitations in the current work

- One nerve model type and simplified structure
- One head model
- Neural target
2. CNS thresholds: Extended Intercomparison (on-going)

- 5 considered “classical” models of the active membrane
- Combined with the SEENN-model (†)
- TMS exposure in hand motor area

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<td>Schwarz-Reid-Bostock</td>
<td>SRB</td>
<td>Human nerve</td>
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Internal Electric Field [V/m]

Excitation Threshold

251 cortical pyramidal axons
2. CNS thresholds:

**Extended Intercomparison (on-going)**

- Excitation thresholds for 251 cortical pyramidal axons

- Next: derivation of distribution/statistical results for uniform exposure
2. CNS thresholds: Extended Intercomparison (related studies)

- Main factors affecting the stimulation (†)

2. CNS thresholds: Extended Intercomparison (related studies)

- Neuronal Targeting (inter-variability) (†)

- Variability in targets area of pyramidal neurons (finger)
- Variability of experimental and computational activation threshold (30% to 60% of maximum stimulation output, $R^2 = 0.60$)
- Morphology (neural curvature): variability of 20% of activation threshold

2. CNS thresholds: Extended Intercomparison

- Excitation thresholds depend strongly on the used membrane model.
- Dependence of excitability on the waveform, e.g., CRRSS model has higher rheobase than the SRB model but lower chronaxie.
- Preliminary results indicate the ‘standard’ SENN-model with HH-dynamics is relatively conservative as compared with the CRRSS, SE and SRB membrane models.
3. Summary and future work (1)

Extended intercomparison

✓ Whole hand motor area

✓ Different nerve models
  • Single cable models (HH, FH, CRRSS, SE, SRB)
  • Double cable (MRG) model
  • Unmyelinated fibres

❖ Determination of dosimetric reference levels
  • Most conservative versus accurate/reasonable neuron model
  • Which percentile (minimum, median, …) of simulated excitation thresholds?

❖ Different head models
3. Summary and future work (2)

Extended intercomparison

- Simplified versus more realistic models:
  - Axons versus morphologically realistic neurons (including dendritic trees, soma, collaterals)
- Neural activation derived from different EMF-solvers
- Anisotropy and dispersion effects (electric field computation)
WG4: Thresholds in CNS

Thank you
Definition of incident power density to correlate surface temperature elevation

WG 5 under IEEE/ICES TC95/SC6 in cooperation with TC34
IEEE ICES TC95 SC6 meeting
18/05/2020

Dr. Walid EL HAJJ
Outlines

- Rationales behind this WG
- Summary of the WG studies
- Candidates of Incident Power Density Definitions
- Assessment Methodology
- Modeling Scenarios
- Evaluation Approaches
- Illustration of Results Template
- Illustration of Evaluation results and conclusions
- Incidence Angle effect
Rationales behind the WG

- International guidelines/standards for EM field exposure above 6 GHz have been recently updated but still some gaps of knowledge in terms of limits and metrics

- Incident Power Density is the metric used for exposure reference level above 6 GHz. For an exposure limit this quantity is generally spatially and time averaged

- Two definitions or averaging methods for (IPD) are possible:
  1. In the first method only normal component of IPD vectors crossing the surface are used.
  2. In the second method IPD vectors magnitude (norm) are averaged over an area independently from the orientation.

- In the near field and for oblique incidence, these definitions lead to different values with significant differences in some exposure conditions

- Correlation with the temperature elevation is necessary to decide on the best definition of incident power density

- This is the scope of the WG created in the objective to study the definition of incident power density in the near field to correlate surface temperature elevation
Summary of the WG studies

- The main study was based on EM and thermal simulation of different sources at different frequencies, distances and scenarios in order to compare incident power density results using both definitions.

- After obtaining the IPD and T distributions for all exposure conditions, the corresponding correlation coefficients and the heating factors using both definitions have been analyzed.

- As the difference between both definitions is also related to the incidence angle, the effect of the oblique incidence have been studied using modeling and thermographic measurement.

- Finally, the measurement AHG group have performed IPD measurement using both definitions in different exposure conditions. The goal was to show the difference in real compliance measurement environment and establishing the correlation with some modeling scenarios.
Candidates of IPD Definitions

1. Definition using the normal component of Incident Power Density

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

Physically, it is the energy flow (or the energy flux leaving the region)

2. Definition using the three components of Incident Power Density

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

While Definition (2) does not have a clear physical meaning, it is conservative relative to (1) and, when evaluated in free space without the body present, might better estimate the incident power density that will contribute to thermal elevation once a body is introduced.
Assessment Methodology

In order to compare the two definitions:

1. Different exposure conditions i.e. modelling scenarios has been defined.
2. An EM simulation has been performed for each scenario in free space then in presence human block model.
3. A thermal calculation has been performed for each scenario in presence of human block model using the SAR values obtained from 2.
4. PD and temperature distributions as well as heating factors are obtained and analysed according to a defined evaluation approach.
5. Effect of Oblique incidence has been studied using simulations and thermographic measurement.
Modeling Scenarios (steps 1, 2 and 3) of slide 6

Exposure Conditions

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EM Models and Thermal Settings

Two separate EM calculations were performed by each organization for each modeling scenario. First, the IPD in free-space was calculated without the body present. Then, the simplified human block model was introduced, and field levels in tissue were calculated. In this latter case, the SAR, is used as the input parameter for the temperature increase evaluation.

\[ c(r)\rho(r) \frac{\partial T(r,t)}{\partial t} = \nabla \cdot \left( \kappa(r) \cdot \nabla T(r,t) \right) + \rho(r) \text{SAR}(r) + A(r, t) - B(r, t)(T(r, t) - T_b(r, t)) \]
Evaluation approaches

A- Results and Data Grouping
After obtaining all the computed peak values of incident $PD$ (including the spatial average values $sPDn$ and $sPDtot$ using both definitions respectively averaged over 1 cm$^2$ and 4 cm$^2$) and temperature increase $\Delta T$ for the different simulation scenarios as well as heating factors, the data have been collected grouping them by the institution/research group, EM source, frequency of the EM signal and finally by the distance of the source and the body model. Since all groups have provided data for the dipole simulations, for the sake of homogeneity, the analysis have been executed on two macrogroups or data sets: 1- dipole source, all simulated distances and frequencies; 2- All sources, all simulated scenarios.

B- Heating Factor Analysis
The HFs have been analysed grouping them by institution/research group. In this way, the average value ($\mu_{HF}$) and standard deviation ($\sigma_{HF}$) have been computed for each of four metrics, i.e. two IPD definitions and two averaging areas 1 and 4 cm$^2$. The same has been repeated considering the all data set. Generally, the set of heating factors obtained from sufficient number of data points should have close to normal distribution, then a smaller value of standard deviation $\sigma_{HF}$ indicates which $PD$ metric best correlates with $\Delta T$. The standard deviation of all heating factors have been calculated and compared using both definitions.

C- Correlation Analysis
The computation of Pearson’s correlation coefficients has been performed to evaluate the linear correlation between the peak $psPD$ data sets (different metrics) and peak $p\Delta T$. This has been performed for all data groups defined in A. A distinction has been highlighted between data coming from simulations with $d = 2 \text{ mm}$ and data from all other simulation scenarios ($d \geq 5 \text{ mm}$), to evaluate possible influence very close distance phenomena.

$$\tau_{lk} = \frac{Cov(psPD_l \text{ avg.} k, p\Delta T)}{\sigma(psPD_l \text{ avg.} k)\sigma(p\Delta T)}, \quad l = n, tot, \quad k = 1, 4$$

Both Definitions Two averaging Areas
Illustrations of results template step 4 of slide 6
(Example Dipole Results by Organization 2)

Power Density and Temperature Distribution

Heating Factor
The analysis of correlation coefficients, shows that, in general, the spatial averaged power density metrics for norm component provide higher correlation than that obtained with the normal component. However, the correlation coefficients for both definitions are relatively close which indicate that both definitions correlate “quiet well” with temperature elevation. It can be seen that excluding the data for the distance < 5 mm, improve the correlation coefficient. This is an indicator about the applicability limitation of the incident power density metric for closer distance. However the metric decisions is not in the scope of this group.

<table>
<thead>
<tr>
<th>All Data</th>
<th>$r_{n1}$</th>
<th>$r_{tot1}$</th>
<th>$r_{n4}$</th>
<th>$r_{tot4}$</th>
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<tbody>
<tr>
<td>Whole set</td>
<td>0.788</td>
<td>0.819</td>
<td>0.709</td>
<td>0.794</td>
</tr>
<tr>
<td>$d \geq 5 \text{ mm}$</td>
<td>0.858</td>
<td>0.854</td>
<td>0.766</td>
<td>0.774</td>
</tr>
</tbody>
</table>

- $r_{n1}$ is the Pearson’s coefficient of the pair ($psPD_{n \text{ avg.1}}$, $p\Delta T$);
- $r_{tot1}$ is the Pearson’s coefficient of the pair ($psPD_{tot \text{ avg.1}}$, $p\Delta T$);
- $r_{n4}$ is the Pearson’s coefficient of the pair ($psPD_{n \text{ avg.4}}$, $p\Delta T$);
- $r_{tot4}$ is the Pearson’s coefficient of the pair ($psPD_{tot \text{ avg.4}}$, $p\Delta T$).
The analysis of HF samples shows that, the smallest $\sigma_{HF}$ are the ones corresponding to $sPD_{tot}$ metrics. This may suggest that $\Delta T$ correlates better with $sPD_{tot}$ rather than $sPD_n$. However the difference is not very significant which may indicate that both definitions describe in a close manner the temperature elevation. Having more statistical data e.g. using heating factor distributions instead of the peaks increase the significance degree of the conclusions based on the standard deviation calculation.
Incidence Angle effect by Modeling

NiTech: **Beam angles**: 0, 15, 30, 45, 60, 75 (for TM cases), 80 (for TM cases)  
**Polarization**: TE, TM  
**Antenna array**: 1×4, 1×8 dipole array  
**Frequency**: 28GHz  
**Distance from array center to skin**: 15 mm (TE, 4-element), 30 mm (TM, 4-element), 45 mm (TE & TM, 8-element)

These figures show that the heating factors at different beam directions for TE- and TM-like polarized waves, respectively. As shown in TE figure (the left), the heating factors derived in 2D analysis decrease with the increase of the beam angle. **The norm of IPD is larger than that of normal component and its difference becomes large with the increase of the beam angle**. The heating factors for 3D analysis are generally smaller than those of 2D analysis as expected, because of the field nonuniformity. As shown in TM figures (to the right), there exist some plots, whose heating factors are 3-4 times higher than those of the others. These plots correspond to those of the patch antenna array on the ground plane, with a narrow beam towards the human body. In such cases, due to the reflection between the human (flat surface) and antenna (10 mm separation), the tendency is different from simple antenna (dipole arrays). In addition, around 80 degree, enhancement of the heating factor is observed because of the Brewster’s angle, especially for that of the normal component. It is around 0.02 °C·m²/W, which is ~60% higher than that of 0.012 °C·m²/W at normal incidence (2D analysis). This suggests that if the heating factor derived based on the normal component is used for safety assessment, possibly, some underestimation can be expected. In such a case, somewhat higher heating factor should be used to provide conservative assessment. However, for the antenna in very close vicinity of the human body, the distance from the antenna array to the surface human body becomes large for larger incident angle. Thus, larger output power is needed for a certain temperature rise.
Incidence Angle effect by Thermographic Measurement

Exposure scenario 1: the phantom aligned at boresight of the antenna.
Exposure scenario 2: the phantom tilted 30° from the boresight of the antenna

The exposure plane is at 70mm distance from the EUT which can be considered as far-field condition at 60 GHz. This explain why for the exposure scenario 1 (normal incidence) both definitions lead to the same values. However for exposure scenario 2 that can be considered as oblique incidence the two definitions leads to different values confirming that the difference is impacted by the non-normal incidence even in the far field.
Next Steps and expected Output

- PAR submitted for IEEE Guide
- Several papers under preparation
## Participants

<table>
<thead>
<tr>
<th>Member</th>
<th>Name</th>
<th>e-mail</th>
</tr>
</thead>
<tbody>
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<td>Valerio De Santis</td>
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<td>12</td>
<td>Quirino Balzano</td>
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<td>13</td>
<td>Alexander.PROKOP</td>
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<td>Kevin Graf</td>
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</tbody>
</table>
IEEE/ICES TC95
Task Force 2 – Uncertainty of low-frequency dosimetry in segmented models

SAR evaluation in learning-based smoothed head models

Essam Rashed, Yinliang Diao, Akimasa Hirata
Nagoya Institute of Technology, Suez Canal University, South China Agriculture University
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TF2: Uncertainty of LF dosimetry in segmented models

- **SCOPE:** Resolve uncertainties related to numerical models that calculate electric fields induced within the body by external electromagnetic fields or contact currents, as well as thresholds of human response to the spatial and temporal characteristics of the induced fields and temperature.

- **Co-Chairs:** Essam Rashed (SCU, Egypt) and Yinliang Diao (SCAU, China)

- Within this general scope, we consider unresolved issues raised in the research agenda of the IEEE ICES (Reilly and Hirata, 2016)

### 2.1. Measurement of tissue conductivity

Tissue conductivity is a crucial element in induction modeling. The number of measurements for tissue conductivity is limited; measured data of Gabriel *et al.* (1996) are used as a *de facto* standard at frequencies above 10 MHz. Gabriel *et al.* (2009) also reported revised data for frequencies below 1 MHz. Further measurements are needed.

### 2.3. Numerical artifacts

Computations with human voxel models are subject to extraneously large ‘staircasing’ artifacts at the interfaces of regions of widely differing conductivity, especially at air/skin interfaces. Researchers differ as to the appropriate method for treating these artifacts. Dimbylow (2005) discarded the largest 1% of induced field values within the voxels of each organ as a mitigation that was originally derived for a sphere by Dawson *et al.* (2001).
TF2: Uncertainty of conductivity estimate
Introduction

- In electromagnetic dosimetry applications, the use of computational human models that imitate human anatomy is essential.

- Non-invasive brain stimulation is a common clinical application. However, it is challenging to accurately compute the electric field in specific brain region.

- The common procedure is to use segmentation then assign uniform conductivity (or other dielectric properties) values within each tissue. This approach is non-realistic and could lead to incorrect computations and artifacts.

- We investigate how to use of machine learning (particularly, deep learning) methods to estimate dielectric properties directly from anatomical images. We validate this approach using SAR computations for dipole antenna located close to subject head.
Human head models

- The current standard pipeline for human head modeling begins with the acquisition of anatomical images followed by intensive segmentation of different tissue compositions.
- Therefore, a uniform tissue conductivity is assigned to each annotated tissue.
- Challenges
  - Segmentation of non-brain tissues is difficult (low-contrast/limited region).
  - Structural MRI is known for gray scale variations.
  - Inter- and intra-subject variability.
- In a previous study, we proposed ForkNet as a deep learning tool for automatically head model generation\(^3\).

\(^3\) Rashed et al., *NeuroImage*, 2019
Deep Learning

- Deep learning is a promising machine learning technology that lead to remarkable impact in big data analysis and understanding.

- In image segmentation, convolutional neural networks (CNN) is now known as the state-of-the-art technique.

- CNN is designed as a sequence of different image (sub-image) filters that is connected in a pipeline known as network. The network filter parameters (features) are calculated and optimized using training data. Then used in testing of new (not used in the training) images.

- Although, several studies have used deep learning in brain segmentation, this is the first study to estimate dielectric properties from structural MRI using deep learning.
How it works

- MRI (T1)
- MRI (T2)

Anatomical images

Segmented model

Tissue-based values

Segmentation parameters

Conductivity

Permittivity

Electrical properties

Radio frequency

900MHz
3.0GHz

Learning-based architecture
CondNet Architecture

Source code is available here: https://github.com/erashed/CondNet
Data & preprocessing

- 18 subjects (T1/T2) from the NAMIC: Brain Multimodality (10 training & 8 testing).
- Semi-automatic method was used to segment into 13 tissues.
- Uniform dielectric properties are assigned and normalized:

\[
\tilde{\sigma}^r = \frac{1 - \tau_\sigma}{\max_n(\sigma_n^r)} \sigma^r, \quad \tilde{\varepsilon}^r = \frac{1 - \tau_\varepsilon}{\max_n(\varepsilon_n^r)} (\varepsilon^r - 1), \quad \tilde{\rho} = \frac{1 - \tau_\rho}{\max_n(\rho_n)} \rho,
\]

- Network is training using slices over different directions (axial, sagittal and coronal).
- Cross-entropy loss function is optimized using ADAM algorithm (50 epochs, batch=2)
Radio-frequency exposure scenario

- Head is exposed to a dipole antenna at radio frequencies.
- The radiation source (power 1 w) is a half-wavelength dipole antenna located at 20 mm from the scalp close to the temporal lobe.
- Finite-difference time-domain (FDTD) method.
- The antenna lengths are 15.7, 7.9, and 4.7 cm at 0.9, 1.8, and 3.0 GHz, respectively.
Results

Sample result of a subject (case01039). Anatomical images (top) and corresponding physical properties (bottom) computed using the standard and learning-based approaches at 0.9 GHz. The color scale is defined as \([a, b] = [0.0, 3.0], [1.0, 70.0],\) and \([800, 1500]\) for \(\sigma, \varepsilon,\) and \(\rho,\) respectively.
Results

Physical properties computed using the standard and proposed (learning-based) approaches at different radio-frequencies. The top left shows the anatomical images. The top right shows the density maps (kg m$^{-3}$). The bottom left and right represent the conductivity (S m$^{-1}$) and relative permittivity maps at 0.9, 1.8 and 3.0 GHz frequencies, respectively.
Variability (tissue-wise)

Standard and learning-based dielectric properties and tissue-density values of the different head tissues in eight subjects computed at different frequencies. (a) Electrical conductivity, (b) relative permittivity, and (c) tissue density. The color bars represent the constant standard values, and the black lines indicate the learning-based value range (mean±std). The doughnut chart in (d) shows the average volume ratio of each tissue. Tissue annotation in the standard approach is used as the golden-truth segmentation.
SAR studies

SAR maps of one subject at different orientations computed using the standard and learning-based approaches with the corresponding anatomical image for frequency of 0.9 GHz.
SAR studies

Axial  Sagittal  Coronal

900MHz

1.8GHz

3.0GHz

SAR (W/kg)

10.0

0.0

standard  learning-based
SAR studies

Truncated coronal slices of the computed SAR maps of the eight subjects computed using the standard (top) and learning-based (bottom) approaches.

Table 3. Absolute error ($E$) of SAR values for different subjects at different frequencies ($\times 10^{-2}$).

<table>
<thead>
<tr>
<th>#</th>
<th>Subject</th>
<th>900 MHz</th>
<th>1.8 GHz</th>
<th>3.0 GHz</th>
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<td>1</td>
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<td>3.200</td>
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<tr>
<td>4</td>
<td>Case01028</td>
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<tr>
<td></td>
<td>Average</td>
<td>5.062</td>
<td>3.386</td>
<td>2.529</td>
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</table>
Conclusion

- A novel CNN architecture is proposed automatic estimation of non-uniform dielectric properties from anatomical MRI scans.
- High consistency between standard values (uniform) and learning-based estimated values (non-uniform) is observed.
- Non-uniform dielectric properties reduce the artifacts known to occurs due to staircasing around edge regions (i.e. smooth pattern).
- Computed SAR values present a high consistent and more smooth patterns.
- No segmentation is required.
- Limitation: non-isotropy properties is not considered (--> future extensions)
Thank you

More details can be found here:

Source code is available here: https://github.com/erashed/CondNet
Inter-individual variations in induced E-field at ELF

Marco Soldati and Ilkka Laakso

Aalto University, Finland

Ilkka Laakso
18 May 2020
Dosimetric limits at 50 Hz

ICNIRP (2010)
Basic restrictions in the CNS:
100 mV/m and 20 mV/m (occupational and general public)

IEEE ICES standard
Dosimetric reference limits in the brain:
44.2 mV/m and 14.7 mV/m (restricted and unrestricted)
Derivation of reference levels

**IEEE ICES standard**
- Elliptical induction model => 2.71 mT and 0.904 mT @ 50 Hz

**ICNIRP guidelines**
- Dosimetry modelling in NORMAN and NAOMI (Dimbylow 2005) and dosimetric uncertainty factor of 3 => 1 mT and 0.2 mT

**Problem:** No data on the variability between individuals (only two anatomical models)

**Objective:** Quantify inter-individual variability in the induced electric field
Study design

**Exposure condition:** Uniform magnetic field (1 mT @ 50 Hz) in three orthogonal directions:
- AP: Front to back
- LAT: Lateral
- TOP: Top to bottom

**Models:** 118 MRI-based head models (80 M, 38 F, age: 28 ± 9 years)
- FEM using 0.5 mm uniform cubical grids
- Electrical conductivity values obtained from [Dimbylow, 2005]

**Postprocessing:**
- Induced electric field averaged over 2 mm x 2 mm x 2 mm cubes.
- 99th percentile value calculated for each tissue.

---

Dimbylow P 2005 Development of the female voxel phantom, NAOMI, and its application to calculations of induced current densities and electric fields from applied low frequency magnetic and electric fields *Phys Med Biol* 50(6) 1047–70
Individual E-field distributions
Effects of age and skull volume

The open-source programing language R was used for statistical analysis

Effect of gender not significant

Aalto University
School of Electrical Engineering
Age-related changes in the brain

(a) CSF volume (litres) vs Age (yrs) for females (F) and males (M).
(b) GM volume (litres) vs Age (yrs).

Aalto University
School of Electrical Engineering
Comparison with the induction models in the standard/guidelines

Our data for LAT exposure: \(22.1 \pm 2.1\) mV/m per 1 mT

Elliptical induction model (IEEE C95.6-2002): \(16.3\) mV/m per 1 mT
  - 2.7 standard deviations below the mean => outlier

Dimbylow (2005), cited in the ICNIRP (2010) guidelines:
NORMAN: \(33.0\) mV/m and NAOMI: \(31.4\) mV/m
  - 5.1 and 4.3 standard deviations above the mean => outliers
Why is NORMAN an outlier?

We used the same conductivity values as Dimbylow (2005) and the same procedure for calculating the 99th percentile electric field. Repeating the calculations using the NORMAN model, the induced electric field values were identical to those reported by Dimbylow.
Induced E-field in NORMAN

2 mm resolution: produces overestimation

Unusually high electric field in the frontal part of the brain

Our data (exemplary subject)
Conclusions

99th percentile electric fields calculated in 118 individual head models showed relatively small variability
  • Standard deviation approximately 10% of the mean

Exposure in the lateral direction induces the highest electric field
  • Higher induced electric field in older individuals and larger heads

Induction models used by both IEEE ICES and ICNIRP are both outliers compared to our data
  • Elliptic induction model: underestimation
  • NORMAN and NAOMI: overestimation

Large degree of conservativeness in the ICNIRP reference levels
  • The basic restriction (100 mV/m) is 36.6 SDs above the mean (22.1 ± 2.1 mV/m) for reference level exposure (1 mT @ 50 Hz)
## Summary statistics

### 99th percentile

<table>
<thead>
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<th>AP</th>
<th>LAT</th>
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<tr>
<td>LTI</td>
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<tr>
<td>SD [CI]</td>
<td>1.4 [1.2, 1.6]</td>
<td>2.1 [1.9, 2.4]</td>
<td>1.3 [1.1, 1.5]</td>
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<tr>
<td>UTI</td>
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<tr>
<td>Maximum</td>
<td>21.2</td>
<td>28.3</td>
<td>20.4</td>
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</table>

### 99.9th percentile

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<td>LTI</td>
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<tr>
<td>SD [CI]</td>
<td>1.9 [1.7, 2.2]</td>
<td>5.0 [4.4, 5.7]</td>
<td>1.8 [1.6, 2.1]</td>
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<tr>
<td>UTI</td>
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<td>36.7</td>
<td>22.7</td>
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<tr>
<td>Maximum</td>
<td>26.3</td>
<td>43.6</td>
<td>25.3</td>
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</table>

### 100th percentile

<table>
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<td>26.4</td>
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<tr>
<td>LTI</td>
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<td>4.3 [3.8, 4.9]</td>
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<tr>
<td>UTI</td>
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<td>51.6</td>
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<tr>
<td>Maximum</td>
<td>39.1</td>
<td>60.6</td>
<td>46.9</td>
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</tbody>
</table>
Non-uniform exposure to pulsed LF fields
Outline

1) The case study
2) Formulation
   hypothesis and validation
3) Numerical artifacts
   metrics
4) Results
The case study (1/2)

A portable welding gun

Worst case: Vertical working condition
The case study (2/2)

Technology:
MFDC
Medium Frequency Direct Current
The formulation used (1/3)

Scalar Potential Finite Difference (SPFD)

\[ \nabla \cdot (\sigma \nabla \varphi) = -\nabla \cdot (j\omega\sigma \vec{A}) \]

- Global (integral) variables
- Algebraic form of the differential operators

\[ G^T M_\sigma G\varphi = -j\omega G^T M_\sigma a \]
The formulation used (2/3)

\[ G^T M_\sigma G \varphi = -j\omega G^T M_\sigma a = -j\omega G^T M_\sigma a_n I \]

Introduction of an effective sigma for the j-th tissue [*]:

\[ \sigma_{eq}^j = \frac{\sum_{f=0}^{f_{max}} I(f) \sigma_j(f)}{\sum_{f=0}^{f_{max}} I(f)} \]

Thanks to the effective sigma with the solution of only one linear system it is possible to obtain the complete solution in time domain knowing the spectrum of the current.

The formulation used (3/3)

\[ G^T M_\sigma G \varphi = -j\omega G^T M_\sigma a = -j\omega G^T M_\sigma a_n I \]

\[ G^T M_{\sigma_{eq}} G \left( \begin{array}{c} \varphi \\ j\omega I \end{array} \right) = -G^T M_{\sigma_{eq}} a_n \]

For a given angular frequency:

\[ \omega, \ I_\omega \Rightarrow \varphi(\omega) = j\omega I_\omega x_n \Rightarrow E(\omega) \xrightarrow{\text{IFFT}} E(t) \]
Assessment of pulsed fields (1/2)

- IEEE:
  - Peak restriction
  - Restriction of time derivative of B-field
  - Fourier based restriction

- ICNIRP
  - Equivalent frequency method
  - Fourier based restriction
  - Weighted Peak Method
Assessment of pulsed fields (2/2)

- IEEE:
  - Peak restriction
  - Restriction of time derivative of B-field
  - Fourier based restriction

- ICNIRP
  - Equivalent frequency method
  - Fourier based restriction
  - Weighted Peak Method

Input field \( \rightarrow \) WPM \( \rightarrow \) Exposure Index

\( < 1 \) for compliance
Validation of the procedure (1/1)

Comparison with not-simplified formulations
Numerical Artifacts (1/1)

Discretization error, staircasing

Field singularities
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.

In Table 1, the *in situ* electric field DRL applies to the rms electric field strength measured in the direction and location providing the maximum *in situ* electric field vector (vector magnitude) over a 5 mm linear distance. The averaging time for an rms measurement is 0.2 s for frequencies above 25 Hz. For lower frequencies, the averaging time is such that at least 5 cycles are included in the average but with a maximum of 10 s. DRLs expressed in Equation (1) apply to frequencies in the range of 0 Hz to 5 MHz.
C95.6, 0 – 3 kHz (2002)

where $E_j$ 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.

C95.1, 0 – 300 GHz (2019)

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ICNIRP 2010 LF Guidelines

Spatial averaging of induced electric field

When restricting adverse effects of induced electric fields to nerve cells and networks, it is important to define the distance or volume over which the local 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 $99^{th}$ percentile value of the electric field is the relevant value to be compared with the basic restriction.
Spatial averaging of induced electric field

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Percentile metrics:
1) 99\textsuperscript{th} percentile (ICNIRP 2010)

2) 99.9\textsuperscript{th} percentile (recent literature)

Statistical and adaptive metrics:

4) Extrap. 2020 [31]

---


Results: 1 x 1 x 1 mm³ model

<table>
<thead>
<tr>
<th>metric</th>
<th>Gray Matter</th>
<th>Fat</th>
<th>SAT</th>
<th>Skin</th>
<th>Spinal Cord</th>
</tr>
</thead>
<tbody>
<tr>
<td>El(B-field)</td>
<td>0.271</td>
<td>4.027</td>
<td>4.137</td>
<td>4.236</td>
<td>1.729</td>
</tr>
<tr>
<td>El(E-field) max</td>
<td>0.178</td>
<td>1.540</td>
<td>1.689</td>
<td>1.923</td>
<td>0.116</td>
</tr>
<tr>
<td>El(E-field) max (2 x 2 x 2 mm³ averaging)</td>
<td>0.141</td>
<td>1.440</td>
<td>1.538</td>
<td>1.147</td>
<td>0.080</td>
</tr>
<tr>
<td>El(E-field) max (5 mm line averaging)</td>
<td>0.178</td>
<td>1.540</td>
<td>1.689</td>
<td>1.118</td>
<td>0.116</td>
</tr>
<tr>
<td>El(E-field) 99.9th</td>
<td>0.072</td>
<td>0.745</td>
<td>0.605</td>
<td>0.556</td>
<td>0.075</td>
</tr>
<tr>
<td>El(E-field) 99.9th (2 x 2 x 2 mm³ averaging)</td>
<td>0.061</td>
<td>0.735</td>
<td>0.598</td>
<td>0.544</td>
<td>0.056</td>
</tr>
<tr>
<td>El(E-field) 99th</td>
<td>0.046</td>
<td>0.411</td>
<td>0.321</td>
<td>0.309</td>
<td>0.045</td>
</tr>
<tr>
<td>El(E-field) 99th (2 x 2 x 2 mm³ averaging)</td>
<td>0.043</td>
<td>0.408</td>
<td>0.318</td>
<td>0.308</td>
<td>0.039</td>
</tr>
<tr>
<td>El(E-field) extrap 2018</td>
<td>0.081</td>
<td>0.846</td>
<td>0.700</td>
<td>0.631</td>
<td>0.116</td>
</tr>
<tr>
<td>El(E-field) extrap 2018 (2 x 2 x 2 mm³ averaging)</td>
<td>0.067</td>
<td>0.824</td>
<td>0.681</td>
<td>0.603</td>
<td>0.062</td>
</tr>
<tr>
<td>El(E-field) extrap 2020</td>
<td>0.108</td>
<td>1.104</td>
<td>1.050</td>
<td>0.917</td>
<td>0.116</td>
</tr>
<tr>
<td>El(E-field) extrap 2020 (2 x 2 x 2 mm³ averaging)</td>
<td>0.089</td>
<td>1.027</td>
<td>0.867</td>
<td>0.799</td>
<td>0.068</td>
</tr>
</tbody>
</table>
Results: 2 x 2 x 2 mm³ model

<table>
<thead>
<tr>
<th>metric</th>
<th>Gray Matter</th>
<th>Fat</th>
<th>SAT</th>
<th>Skin</th>
<th>Spinal Cord</th>
</tr>
</thead>
<tbody>
<tr>
<td>EI(B-field)</td>
<td>0.242</td>
<td>3.964</td>
<td>4.072</td>
<td>4.355</td>
<td>1.620</td>
</tr>
<tr>
<td>EI(E-field) max</td>
<td>0.119</td>
<td>1.360</td>
<td>1.409</td>
<td>3.540</td>
<td>0.075</td>
</tr>
<tr>
<td>EI(E-field) max (5 mm line averaging)</td>
<td>0.119</td>
<td>1.360</td>
<td>1.409</td>
<td>3.540</td>
<td>0.075</td>
</tr>
<tr>
<td>EI(E-field) 99.9th</td>
<td>0.062</td>
<td>0.717</td>
<td>0.587</td>
<td>0.564</td>
<td>0.061</td>
</tr>
<tr>
<td>EI(E-field) 99th</td>
<td>0.042</td>
<td>0.396</td>
<td>0.316</td>
<td>0.305</td>
<td>0.041</td>
</tr>
<tr>
<td>EI(E-field) extrap 2018</td>
<td>0.069</td>
<td>0.808</td>
<td>0.675</td>
<td>0.614</td>
<td>0.075</td>
</tr>
<tr>
<td>EI(E-field) extrap 2020</td>
<td>0.095</td>
<td>1.023</td>
<td>0.940</td>
<td>0.790</td>
<td>0.075</td>
</tr>
</tbody>
</table>
## Results: comparison in the SAT

<table>
<thead>
<tr>
<th>metric</th>
<th>$1 \times 1 \times 1 \text{ mm}^3$</th>
<th>$2 \times 2 \times 2 \text{ mm}^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>EI(B-field)</td>
<td>4.137</td>
<td>4.072</td>
</tr>
<tr>
<td>EI(E-field) max</td>
<td>1.689</td>
<td>1.409</td>
</tr>
<tr>
<td>EI(E-field) max (2 $\times$ 2 $\times$ 2 mm$^3$ averaging)</td>
<td>1.538</td>
<td>n.a.</td>
</tr>
<tr>
<td>EI(E-field) max (5 mm line averaging)</td>
<td>1.689</td>
<td>1.409</td>
</tr>
<tr>
<td>EI(E-field) 99.9th</td>
<td>0.605</td>
<td>0.587</td>
</tr>
<tr>
<td>EI(E-field) 99.9th (2 $\times$ 2 $\times$ 2 mm$^3$ averaging)</td>
<td>0.598</td>
<td>n.a.</td>
</tr>
<tr>
<td>EI(E-field) 99th</td>
<td>0.321</td>
<td>0.316</td>
</tr>
<tr>
<td>EI(E-field) 99th (2 $\times$ 2 $\times$ 2 mm$^3$ averaging)</td>
<td>0.318</td>
<td>n.a.</td>
</tr>
<tr>
<td>EI(E-field) extrap 2018</td>
<td>0.700</td>
<td>0.675</td>
</tr>
<tr>
<td>EI(E-field) extrap 2018 (2 $\times$ 2 $\times$ 2 mm$^3$ averaging)</td>
<td>0.681</td>
<td>n.a.</td>
</tr>
<tr>
<td>EI(E-field) extrap 2020</td>
<td>1.050</td>
<td>0.940</td>
</tr>
<tr>
<td>EI(E-field) extrap 2020 (2 $\times$ 2 $\times$ 2 mm$^3$ averaging)</td>
<td>0.867</td>
<td>n.a.</td>
</tr>
</tbody>
</table>
Thank you for the attention
In situ Electric Field in Different Body Parts For Exposure to Uniform Magnetic Field

Keishi Miwa\textsuperscript{1}, Yosuke Suzuki\textsuperscript{1}, Yinliang Diao\textsuperscript{1,2}, Akimasa Hirata\textsuperscript{1}

Nagoya Institute of Technology
South China Agricultural University
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   • Human Model and Condition
     Simplified model: Cuboids and Ellipses
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3. Result
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     Maximum Internal Voltage
     Distribution of Internal Voltage and Electric field
     Hypothetical formula
   • 2nd Ellipses
   • 3rd Whole Body and Body Parts

4. Conclusion
1. Background and Purpose

**IEEE & ICNIRP trends**
(Exposure Reference Level/Reference Level)

Exposure Reference Level/Reference Level for local exposure has been newly introduced in IEEE C95.1-2019 and ICNIRP guidelines (2020) for practical assessment in RF (> 100 kHz).

In practical scenarios, there are a variety of the magnetic field distribution, which depends on devices (EUTs).

Reference level which depends on the magnetic field distribution is needed to define.

*Wireless power transfer*<br>
*Blower Motor for Air Conditioner*
1. Background and Purpose

IEEE & ICNIRP trends
(Human model)

・ In IEEE C95.6-2002 standard, it mentions about an ellipsoidal induction model for LF exposure.
・ Different (exposure) reference levels are set for different body parts; trunk versus limbs

Even in case of non-uniform exposure, it is confirmed whether external field strength in corresponding body parts exceeds local reference levels which is based on the induction model for uniform exposure.

Local reference level in corresponding body for local exposure is needed to define.

Purpose
To consider the relationship between magnetic field in the human body and internal electric field for uniform exposure.
2. Model and Method - Human Model

The TARO model, which was developed at the National Institute of Information and Communications Technology (NICT).
2. Model and Method - Condition

Exposure Scenario

- Exposure Field Distribution: Uniform
- Magnetic field strength: 0.1 mT
- Vector: \( \hat{y} \)
- Frequency: 100 Hz

Model Condition

1st: Cuboid

\[ (x, y, z) = (0.4, 0.1\sim2, 0.4) \]

2nd: Ellipses (IEEE C95.6-2002)

\[ (x, y, z) = (0.4, 0.4, 0.1\sim2) \]

3rd: Anatomical model (TARO model)
   - Homogeneous (fat)
   - Inhomogeneous model

To consider the relationship between magnetic field and internal electric field.

To confirm whether the above relationship can be applied or not.
2. Model and Method - Computational Method

Scalar-Potential Finite-Difference (SPFD)† method

The scalar potential is calculated by solving simultaneous linear equations. Then the internal electric field is calculated by differencing the scalar potential.

\[ \sum_{n=1}^{6} s_n \varphi_n - \left( \sum_{n=1}^{6} s_n \right) \varphi_0 = j \omega \sum_{n=1}^{6} (-1)^n s_n l_n A_{0n} \]

Equation

The voxel resolution

\[ \delta = 2.0 \text{ [mm]} \]

\[ s_n \left(= \sigma_n \frac{a_n}{l_n} \right) : \text{Edge conductance} \quad \varphi_n : \text{Scalar potential at each node} \]

\[ \sigma_n : \text{Conductivity of one side} \quad \omega : \text{Angular frequency} \]

\[ a_n : \text{Area of one voxel plane} \quad A_{0n} : \text{Magnetic vector potential of voxel edges} \]

\[ l_n : \text{Edge length} \quad n : \text{Node position label} \]

3. Result

1st: Cuboid

**Maximum Internal Voltage Value**

① \((x,y,z) = (0.4, 0.1\sim2, 0.4)\)

② \((x,y,z) = (0.4, 0.4, 0.1\sim2)\)

- Internal voltage doesn’t depend on the length of \(y\) which is same vector of magnetic field.
- Internal voltage rises as a linear function of size of \(z\).

**A**

It is assumed that the internal voltage is determined by area where the magnetic field flows according to Faraday’s law.

\[
\text{Induced voltage} = j \omega BS = j \omega Bxz \quad \cdots \quad (1)
\]

* \(S\) is vertical area against magnetic field vector.
3. Result

1st: Cuboid \((x,y,z)=(0.2, 0.4, 1)\)

**Distribution of Internal Voltage and Electric Field**

1. Internal voltage has the maximum value at **edge** of Cuboids.
2. Internal electric field has the maximum value at the **long side center** of Cuboids.

- **Result**\((x,y,z)=(0.2, 0.4, 0.1)\)

This tendency resembles the case that there are two dipoles at long side.
3. Result

1st: Cuboid

Hypothetical formula

(A) The internal voltage is determined by area where the magnetic field flows according to Faraday's law.

\[ \text{Internal voltage} (V_{in}) = j\omega BS = j\omega Bxz \cdots \cdots (1) \]

(B) The relationship between internal voltage and electric field resembles the case that there are two dipoles at long side.

Voltage of one dipole \( \frac{V_{in}}{2} = \frac{j\omega Bxz}{2} \cdots \cdots (2) \)

Internal Electric field

\[ \text{Internal Electric field} = - \text{grad} (\text{Voltage of one dipole}) = \begin{cases} -\frac{j\omega Bx}{2} & \cdots (3) \quad (x<z) \\ -\frac{j\omega Bz}{2} & \cdots (4) \quad (x>z) \end{cases} \]

E: Internal electric field
3. Result

1st: Cuboid

Comparison of internal electric field between hypothetical formula and SPFD.

<table>
<thead>
<tr>
<th>x [m]</th>
<th>y [m]</th>
<th>z [m]</th>
<th>Emax_Hypothetical formula [mV/m]</th>
<th>Emax_SPFD [mV/m] 100%ile</th>
<th>Hypothetical formula/SPFD [dB]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4</td>
<td>0.4</td>
<td>0.1</td>
<td>3.1</td>
<td>3.1</td>
<td>0.1</td>
</tr>
<tr>
<td>0.4</td>
<td>0.4</td>
<td>0.2</td>
<td>6.2</td>
<td>5.8</td>
<td>0.7</td>
</tr>
<tr>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>12.6</td>
<td>8.4</td>
<td>3.5</td>
</tr>
<tr>
<td>0.4</td>
<td>0.4</td>
<td>0.8</td>
<td>12.6</td>
<td>11.6</td>
<td>0.7</td>
</tr>
<tr>
<td>0.4</td>
<td>0.4</td>
<td>1.6</td>
<td>12.6</td>
<td>12.5</td>
<td>0.0</td>
</tr>
<tr>
<td>0.4</td>
<td>0.4</td>
<td>2.0</td>
<td>12.6</td>
<td>12.5</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Internal electric field can be estimated from Hypothetical formula.

In case of z=x,

<Internal electric field>

The cuboid has **four** dipoles

<Internal voltage>

The voltage at edge of cuboids is 0V

Because voltage cancels each other with adjacent dipole.

→ Maximum voltage of SPFD is lower.
### 3. Result

**<Internal Electric Field>**

Internal Electric Field [V/m]

<table>
<thead>
<tr>
<th>Short side: x</th>
<th>Long side: z</th>
<th>Emax_Hypothetical formula [mV/m]</th>
<th>Emax_SPFD [mV/m] 99.9%ile</th>
<th>Emax_SPFD [mV/m] 99%ile</th>
<th>Hypothetical formula/SPFD [dB]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.34</td>
<td>1.80</td>
<td>8.3</td>
<td>9.9</td>
<td>9.9</td>
<td>1.5</td>
</tr>
<tr>
<td>0.40</td>
<td>0.80</td>
<td>9.8</td>
<td>9.6</td>
<td>9.6</td>
<td>-0.2</td>
</tr>
<tr>
<td>0.34</td>
<td>0.80</td>
<td>8.3</td>
<td>8.7</td>
<td>8.7</td>
<td>0.4</td>
</tr>
<tr>
<td>0.18</td>
<td>0.84</td>
<td>4.4</td>
<td>5.2</td>
<td>5.2</td>
<td>1.5</td>
</tr>
</tbody>
</table>

The difference of internal electric field between SPFD and hypothetical formula is less than 1.5dB.

**Internal electric field of ellipse model can be estimated from Hypothetical formula.**
3. Result

3rd Anatomical model homogeneous (fat) & inhomogeneous model

For leg and arm, it is almost single dipole rather than two dipoles.

<table>
<thead>
<tr>
<th>Taro model</th>
<th>Emax_Hypothetical formula [mV/m]</th>
<th>Emax_SPFD[mV/m]※ A(B)</th>
<th>Emax_Hypothetical/SPFD[dB]※ A(B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>whole body</td>
<td>10</td>
<td>12(17)</td>
<td>1.5(4.6)</td>
</tr>
<tr>
<td></td>
<td>99.9%ile</td>
<td>99%ile</td>
<td>99.9%ile</td>
</tr>
<tr>
<td></td>
<td>99%ile</td>
<td></td>
<td>99%ile</td>
</tr>
<tr>
<td>left arm</td>
<td>2</td>
<td>3(4)</td>
<td>3.5(6)</td>
</tr>
<tr>
<td></td>
<td>99.9%ile</td>
<td>3(3)</td>
<td>3.5(3.5)</td>
</tr>
<tr>
<td></td>
<td>99%ile</td>
<td></td>
<td></td>
</tr>
<tr>
<td>left leg</td>
<td>4</td>
<td>4(5)</td>
<td>0(1.9)</td>
</tr>
<tr>
<td></td>
<td>99.9%ile</td>
<td>4(4)</td>
<td>0(0)</td>
</tr>
<tr>
<td>trunk and head</td>
<td>8</td>
<td>10(14)</td>
<td>1.9(2.9)</td>
</tr>
<tr>
<td></td>
<td>99.9%ile</td>
<td>8(10)</td>
<td>0(1.8)</td>
</tr>
<tr>
<td></td>
<td>99%ile</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

※ A : Result of homogeneous (fat)  B : Result of inhomogeneous model

The difference of internal electric field between SPFD and hypothetical formula is less than 5dB

We need to reconsider the hypothetical formula separately from the simple model (Cuboid & Ellipses).
4. Summary

Purpose

To consider the relationship between magnetic field which exposes the human body and internal electric field for uniform exposure.

Conclusion

According to distribution of internal voltage and electric field distribution,

○ The internal voltage depends on the area where the magnetic field flows.
   → Faraday’s law can be applied to estimate the internal voltage.
      → Internal voltage \( V_{in} = j\omega BS = j\omega Bxz \) ・・・・・ (1)

○ The distribution of internal voltage and electric fields is almost same as voltage and current of dipole.
   → The dipole principle can be applied to estimate the internal electric field.
      → Voltage of one dipole \( = V_{in} = \frac{j\omega Bxz}{2} \) ・・・・・ (2)

      Internal Electric field = -\text{grad}(Voltage of one dipole)

The hypothetical formula can be applied to ellipses.

Future work

To consider
   ・ why human model is different from the phenomenon of cuboid and ellipses.
   ・ whether the above phenomenon can be applied to non-uniform exposure.