Evaluation of Human Exposure Levels around Radio Base Stations in Korea

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Background: Study on EMF & Health Effect

EMF: ElectroMagnetic Field
Background: Frequency Range

Frequency, Hz

10^2 10^4 10^6 10^8 10^10 10^12 10^14 10^16 10^18 10^20

Radio  Microwave  Infrared  Ultraviolet  X-ray

Power Line  AM radio  FM radio  Microwave oven  Heating Lamp  Tanning booth  Medical X-rays

Cell phones

Non-ionizing

Low induced currents
High induced currents
Electronic excitation
Broken bonds

- No proven effect
- Heating
- Photochemical effects
- DNA damage

Ionizing
Background: Basis for Limiting Exposure

Limiting Basis

- **Induced current**
- **Thermal effect, excitation**
- **Thermal effect**

Dosimetric Quantity

- **Current density**
- **SAR**
- **Power density**

Dosimetry: Measurement or determination by calculation of internal electric field strength or induced current density or SAR in humans or animals exposed to EMFs
Background: Safety Limits-1

Basic Restriction

- The fundamental quantities that determine the physiological response of the human body to EMFs: Current density (J), Specific absorption ratio (SAR), Power density (S)
- It applies to a situation with the body present in the field

Reference Level

- Alternative means for determining compliance: Electric field strength (E), Magnetic field strength (H), Equivalent plane power density (S)
- It applies to a situation where the electromagnetic field is not influenced by the presence of a body
Background: Safety Limits-2

ICNIRP: International Committee on Non-Ionizing Radiation Protection

Note 1. Field value is rms and unit of frequency is same with leftmost column
2. The field strength are to averaged over any 6-min period
Background: Field Region

\[ E \perp H \]
\[ Z = \frac{E}{H} \neq Z_0 \]

Measured quantity: SAR

- Reactive near-field
- Radiating near-field
- Radiating far-field

Distance from the source:
- 0
- \( \frac{\lambda}{4} \)
- 2\( D^2/\lambda \)

E or H

Dosimetry in near field

\[ \text{SAR} = \frac{\sigma E_i^2}{\rho} \]

- \( E_i \): rms [V/m], \( \sigma \): conductivity [S/m], \( \rho \): density [kg/m\(^3\)]
Background: Determine the Compliance-2

- Evaluation of maximum permissible exposure in far field
Motivation

- How can we evaluate reasonably the impact of EMF on the human body in far field?
- What method should be used to measure the exposure practically?
Research Issues in Korea

- Spatial averaging: Number of points
- Time averaging: 6 min or others at each point
- Prediction: Possible maximum field level location
- Uncertainty: Probability function

![Diagram showing direct and reflection waves](image)
Spatial Averaging: Previous Status

- Multi-path reflections & Non uniform field distributions
- Natural and Man-made structures
- No global standard regarding number of points

<table>
<thead>
<tr>
<th></th>
<th>Australia</th>
<th>France</th>
<th>Portugal</th>
<th>Belgium</th>
<th>Italy</th>
<th>EN50383</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference height [m]</td>
<td>1.5</td>
<td>0.75</td>
<td>1.1, 1.5, 1.7</td>
<td>-</td>
<td>1.1, 1.5, 1.9</td>
<td>-</td>
</tr>
<tr>
<td>No. of points</td>
<td>5</td>
<td>9</td>
<td>3</td>
<td>6</td>
<td>3</td>
<td>-</td>
</tr>
<tr>
<td>dimension [height*width, m]</td>
<td>1.0</td>
<td>1.0*0.5</td>
<td>-</td>
<td>1.2*0.4</td>
<td>-</td>
<td>0.7*0.4</td>
</tr>
</tbody>
</table>

Deviation = \( \frac{\sum_{i=1}^{n_i} E_i - \sum_{j=1}^{n_j} E_j}{\sum_{j=1}^{n_j} E_j} \)
Spatial Averaging: Previous Study

- By small scale fading: N points have to be independent
- The correlation distance
  - Theoretically 0.4 λ and empirically 0.8 λ
  - Usually 0.5 λ

Error estimation

- Rayleigh model
  \[ p(\gamma) = e^{-\frac{N}{\gamma}} \sum_{j=0}^{N-1} \frac{1}{j!} \left( \frac{N}{\gamma} \right)^j - e^{-N\gamma} \sum_{j=0}^{N-1} \frac{1}{j!} (N\gamma)^j \]

- Rician model (standard deviation)
  \[ p(\gamma) = Q_N \left( \sqrt{\frac{Na^2}{b^2}}, \sqrt{\frac{N}{\gamma}(2 + \frac{a^2}{b^2})} \right) - Q_N \left( \sqrt{\frac{Na^2}{b^2}}, \sqrt{N\gamma(2 + \frac{a^2}{b^2})} \right) \]

Spatial Averaging: Rationale

- Assessed quantity
  - Electric and magnetic field strength or equivalent plane wave power density
- At a given location
  - Diffraction and reflections
  - Different phases and amplitudes
- Spatial variations known as small-scale fading
  - It does not allow a repeatable exposure level
  - We should use an averaging scheme.

![Graph showing electric field strength variations](image-url)
Spatial Averaging: Approach for New Method

- To determine the number of measurement points
  - Imitate the space occupied by human
  - Analysis the spatial variations of electric field strength
- To consider the effect of environments
  - Urban
  - Suburbs
  - Rural

Isotropic Electric Probe

Tripode

Spectrum Analyzer

RS232

GPS Receiver

Computer

1.7 m 1.5 m 1.1 m

1.7 m 1.5 m 1.1 m 0.2 m

1.7 m 1.5 m 1.1 m 0.2 m

1.7 m 1.5 m 1.1 m 0.2 m

---

::: ETRI, The Future Wave :::
# Spatial Averaging: Analysis

- Maximum mean value occur when 6 or 9 points are used in averaging process.

<table>
<thead>
<tr>
<th>No. of points</th>
<th>BS1</th>
<th>BS2</th>
<th>BS3</th>
<th>BS4</th>
<th>BS5</th>
<th>BS6</th>
</tr>
</thead>
<tbody>
<tr>
<td>27 Ave.</td>
<td>0.2866</td>
<td>0.2713</td>
<td>0.2308</td>
<td>0.3514</td>
<td>0.0299</td>
<td>0.0457</td>
</tr>
<tr>
<td>Ave.(-)</td>
<td>0.2888</td>
<td>0.2714</td>
<td>0.2312</td>
<td>0.3616</td>
<td>0.0274</td>
<td>0.0477</td>
</tr>
<tr>
<td>Ave.(0)</td>
<td>0.2835</td>
<td>0.2712</td>
<td>0.2313</td>
<td>0.3511</td>
<td>0.0331</td>
<td>0.0424</td>
</tr>
<tr>
<td>Ave.(+)</td>
<td>0.2874</td>
<td>0.2712</td>
<td>0.2312</td>
<td>0.3616</td>
<td>0.0274</td>
<td>0.0477</td>
</tr>
<tr>
<td>Ave.(-)</td>
<td>0.2867</td>
<td>0.2716</td>
<td>0.2301</td>
<td>0.3457</td>
<td>0.0300</td>
<td>0.0461</td>
</tr>
<tr>
<td>Ave.(0)</td>
<td>0.2826</td>
<td>0.2709</td>
<td>0.2312</td>
<td>0.3590</td>
<td>0.0315</td>
<td>0.0440</td>
</tr>
<tr>
<td>Ave.(+)</td>
<td>0.2881</td>
<td>0.2711</td>
<td>0.2309</td>
<td>0.3835</td>
<td>0.0275</td>
<td>0.0473</td>
</tr>
<tr>
<td>Number of Max. average point</td>
<td>9</td>
<td>6</td>
<td>9</td>
<td>6</td>
<td>9</td>
<td>9</td>
</tr>
</tbody>
</table>

- The more number of base stations we select, the better statistical meanings we can get. However, the purpose of these measurements does not determine the statistical significance (p-value estimation) between “an exposure to EMF from base station antenna” and “that’s impact on the human health” but check the levels of exposure.
Spatial Averaging: Korea’s Method

- Location of the main organs of human and theoretical correlation distance
- Reliable and repeatable exposure assessment

\[ E = \sqrt{\frac{\sum_{i=1}^{N} (\hat{E}_i)^2}{N}} \]

\[ H = \sqrt{\frac{\sum_{i=1}^{N} (\hat{H}_i)^2}{N}} \]

\[ S = \frac{\sum_{i=1}^{N} \hat{S}_i}{N} \]

N: number of points
\( \hat{E}_i \): root mean square

Time Averaging: Previous Status

- Number of points for spatial averaging: 3, 6, 9, 20 points (ITU-T K.61 and IEC62232)
- Measurement time
  - ICNIRP guidelines: Recommend averaged over any 6 min period
  - Frequencies between 100 kHz and 10 GHz.

Time Averaging: Previous Study

- Established biological and health effects
  - Temperature (eyeball) rise of more than 1 degree

<table>
<thead>
<tr>
<th>Tissue</th>
<th>Mass density (kg/m$^3$)</th>
<th>Thermal conductivity (W/m K)</th>
<th>Specific heat capacity (J/Kg K)</th>
<th>Volumetric perfusion (m$^3$/m$^3$s)</th>
<th>Equilibration time (min)</th>
<th>Conductivity (K kg/W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skeletal muscle</td>
<td>1050</td>
<td>0.50</td>
<td>3465</td>
<td>0.9</td>
<td>17</td>
<td>300</td>
</tr>
<tr>
<td>Kidney</td>
<td>1050</td>
<td>0.54</td>
<td>3700</td>
<td>61</td>
<td>0.27</td>
<td>4.4</td>
</tr>
<tr>
<td>Liver</td>
<td>1060</td>
<td>0.52</td>
<td>3600</td>
<td>15</td>
<td>1.1</td>
<td>18</td>
</tr>
<tr>
<td>Adipose tissue</td>
<td>950</td>
<td>0.27</td>
<td>3100</td>
<td>0.5</td>
<td>25</td>
<td>480</td>
</tr>
<tr>
<td>Brain</td>
<td>1040</td>
<td>0.54</td>
<td>3640</td>
<td>7.3</td>
<td>2.2</td>
<td>36</td>
</tr>
<tr>
<td>Blood</td>
<td>1060</td>
<td>0.51</td>
<td>3720</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

- Heat transfer model

\[
\frac{\partial T(x,t)}{\partial t} - \alpha \frac{\partial^2 T(x,t)}{\partial x^2} + \beta (T(x,t) - T_a) = q(x,t)
\]

\[
Max\{\Delta T(t)\} = \sigma L_{SAR}[1 - \exp(-t/\tau)]
\]

\[
L_{SAR} = (10 - 8r), r: \text{exposed mass/total mass}
\]

Time Averaging: Rationale of Time Reduction

The averaging time

- means the appropriate time over which exposure is averaged
- is 6 min at each point
- increases as the number of points increases
- increasing means an increase in cost
- is related to the time constant for partial body heating: present of a human body
- therefore, is not always necessary in all far field assessments

Reference levels at any point

- are evaluated in the absence of a human body
- are intended to be spatially averaged values body of the exposed individual
Time Averaging: Approach and Analysis

- Analyzed the eighteen periods of time from 180 to 10 sec: 10 sec interval

<table>
<thead>
<tr>
<th>Time (sec)</th>
<th>Base station</th>
<th>360</th>
<th>180</th>
<th>60</th>
<th>40</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>109.80</td>
<td>109.79</td>
<td>109.79</td>
<td>109.79</td>
<td>109.80</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>107.07</td>
<td>107.07</td>
<td>107.09</td>
<td>107.07</td>
<td>107.11</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>111.59</td>
<td>111.55</td>
<td>111.60</td>
<td>111.63</td>
<td>111.81</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>92.56</td>
<td>92.36</td>
<td>92.34</td>
<td>92.33</td>
<td>92.56</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>90.41</td>
<td>90.28</td>
<td>90.76</td>
<td>90.84</td>
<td>90.74</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>97.38</td>
<td>97.26</td>
<td>97.39</td>
<td>97.40</td>
<td>97.67</td>
<td></td>
</tr>
</tbody>
</table>

Unit: dBuV/m

- The estimated standard uncertainties: 0.09 ~ 0.40 dB (t-distribution; t_{0.025}=2.05, DoF=29)

<table>
<thead>
<tr>
<th>Base station</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arithmetic average (dBuV/m)</td>
<td>110</td>
<td>117</td>
<td>106</td>
<td>109</td>
<td>114</td>
<td>100</td>
<td>93</td>
<td>107</td>
<td>110</td>
<td>99</td>
</tr>
<tr>
<td>Standard deviation (SD)</td>
<td>0.25</td>
<td>0.62</td>
<td>0.98</td>
<td>0.46</td>
<td>0.39</td>
<td>1.07</td>
<td>0.59</td>
<td>0.40</td>
<td>0.58</td>
<td>0.51</td>
</tr>
<tr>
<td>$T_{r/2}$ (confidence level: 95%, DoF: 29)</td>
<td>2.05</td>
<td>2.05</td>
<td>2.05</td>
<td>2.05</td>
<td>2.05</td>
<td>2.05</td>
<td>2.05</td>
<td>2.05</td>
<td>2.05</td>
<td>2.05</td>
</tr>
<tr>
<td>Standard uncertainty</td>
<td>0.09</td>
<td>0.23</td>
<td>0.36</td>
<td>0.17</td>
<td>0.15</td>
<td><strong>0.40</strong></td>
<td>0.22</td>
<td>0.15</td>
<td>0.22</td>
<td>0.19</td>
</tr>
</tbody>
</table>

DoF: Degree of Freedom
Time Averaging: Korea’s Method

- Compare the SD with uncertainty of measurement drift
  - Between the 360 sec average value and different time periods
  - No overlapping time period: 1~60, 61~120, 121~180, 181~240, 241~300, 301~360 sec
  - Maximum value of SD: 0.58 dB at 10 sec
  - Uncertainty for repeated measurement: 0.4 dB

\[
\begin{align*}
q &= \frac{1}{n} \sum_{j=1}^{n} q_j \\
\sigma(q) &= \sqrt{\frac{1}{n-1} \sum_{j=1}^{n} (q_j - q)^2}
\end{align*}
\]

\[
\sigma(q) = \frac{1}{\sqrt{n}} \sqrt{\frac{1}{n-1} \sum_{j=1}^{n} (q_j - q)^2}
\]

Predicting Formula: Korea’s Method

- Need to predict the possible maximum exposure position

\[ G = 4\pi \frac{U(\theta, \phi)}{P_{\text{in}}} \]

\[ G = 4 \pi U(\theta, \phi) \]

\[ P_{\text{in}} G = 4 \pi U(\theta, \phi) \]

\[ U(\theta, \phi) = r^2 W_{\text{rad}} = r^2 \frac{1}{2} \text{Re}[\vec{E} \times \vec{H}^*] = r^2 \frac{|\vec{E}|^2}{2\eta} \]

\[ U(\theta, \phi) = r^2 \frac{|E_e(r, \theta, \phi)|^2}{2\eta} \]

\[ |E_e|^2_{\text{max}} = \eta \frac{I_0^2}{4\pi^2} \]

\[ U_{\text{max}}(\theta, \phi) = \frac{r^2}{2\eta} \times |E_e|_{\text{max}} = \frac{\eta I_0^2}{8\pi^2} \]

\[ \frac{\eta I_0^2}{2\pi} = P_{\text{in}} G, I_0 = \sqrt{\frac{2\pi P_{\text{in}} G}{\eta}} \]

\[ \bar{E}^t = \hat{a}_e (1 + |\Gamma|) j e^{-j\beta r} \sqrt{\eta P_{\text{in}} G} \left[ \frac{\cos\left(\frac{\beta l}{2} \sin \alpha \right) - \cos\left(\frac{\beta l}{2} \right)}{\cos \alpha} \right] \]

\[ \bar{E}^t = \hat{a}_e (1 + |\Gamma|) j e^{-j\beta r} \sqrt{\eta P_{\text{in}} G} \left[ \frac{\cos\left(\frac{\beta l}{2} \sin \alpha \right) - \cos\left(\frac{\beta l}{2} \right)}{\cos \alpha} \right] \]

\[ \Gamma = \frac{-(e_r' - j 60 \lambda \sigma) \sin \theta_i + \sqrt{(e_r' - j 60 \lambda \sigma) - \cos^2 \theta_i}}{(e_r' - j 60 \lambda \sigma) \sin \theta_i + \sqrt{(e_r' - j 60 \lambda \sigma) - \cos^2 \theta_i}} \]

\[ \theta_i = \sin^{-1}\left( \sin \alpha \ast \left( \frac{h_i + h_r}{h_i - h_r} \right) \right) \]
Evaluating Methods: Protocols and Status

- Depending on the operation state,
  - Put on the market: EN50383 (certification measurement)
  - Put into service (EEM): RRL Notice 2010-64, EN50400
  - Offer a service (In situ): TTAS.KO-06.0125, EN50492, IEC62232

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EEM: Electromagnetic Environment Measurement
Evaluating Methods: Korea’ method for In Situ

- Focused on human beings: human-centric
- Korean standard was established in December, 2006.
- Assume spatially averaged value / Take total exposure ratio (TER) of same frequency
- Only 1 point in any positions within space occupied by human body
Evaluating Methods: Korea’ method for In Situ Evaluation at place of concern

- Where the general public have voiced concerns about EMF
- Reference for the WHO in developing its anticipated Environmental Health Criteria (EHC) on radiofrequency

Uncertainty: Previous study

- Several kinds of uncertainty sources exist
- The rationale of probability function is insufficient
- Divisor of U-shape probability function: $\sqrt{2}$ Rectangular, $\sqrt{3}$ Triangular, $\sqrt{6}$ Normal: 2.0

<table>
<thead>
<tr>
<th>Budget</th>
<th>Uncertainty Source</th>
<th>Probability Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement equipment</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Calibration</td>
<td>Normal</td>
<td></td>
</tr>
<tr>
<td>Isotropy</td>
<td>Normal</td>
<td></td>
</tr>
<tr>
<td>Linearity</td>
<td><strong>Rectangular</strong></td>
<td></td>
</tr>
<tr>
<td>Measurement device</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Noise</td>
<td>Normal</td>
<td></td>
</tr>
<tr>
<td>Power chain</td>
<td>Normal</td>
<td></td>
</tr>
<tr>
<td>Physical parameters</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Drifts in output power of the EUT, probe, temperature and humanity</td>
<td><strong>Rectangular</strong></td>
<td></td>
</tr>
<tr>
<td>Perturbation of the environment</td>
<td></td>
<td><strong>Rectangular</strong></td>
</tr>
<tr>
<td>Influence of the body</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Post processing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spatial averaging</td>
<td></td>
<td><strong>Rectangular</strong></td>
</tr>
</tbody>
</table>

Source: EN50492, 2008
Uncertainty: Rationale

A measured quantity is not measured directly, but is determined from other quantities through a functional relationship

\[ Q = f(R_1, R_2, \ldots, R_N): \text{measured quantity} \]
\[ q = f(r_1, r_2, \ldots, r_N): \text{estimate} \]

Uncertainty: The variance of the mean

\[ s(q) = \frac{s(q_j)}{\sqrt{n}} = \frac{1}{\sqrt{n}} \left[ \frac{1}{n-1} \sum_{j=1}^{n} (q_j - \bar{q})^2 \right]^{\frac{1}{2}} \]
\[ q = \frac{1}{n} \sum_{j=1}^{n} q_j \]

![Diagram showing assessment result, exposure limit, and 95% confidence interval](image)
Uncertainty: Approach & Analysis

- Type A: Be obtained by repeated measurement
- Type B: Be estimated by the data on the calibration or specification sheet

<table>
<thead>
<tr>
<th>Type</th>
<th>Contribution components</th>
<th>Uncertainty sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical parameters</td>
<td>Power drift (measurement drift), Body influence, noise</td>
<td></td>
</tr>
<tr>
<td>Mechanical constraints</td>
<td>Tripod positioning, Mismatch between receiving antenna (or probe) and base station’s antenna</td>
<td></td>
</tr>
<tr>
<td>Post-processing</td>
<td>Spatial averaging</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Type</th>
<th>Contribution components</th>
<th>Uncertainty sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement equipment</td>
<td>Calibration, Power receiver, Isotropy /linearity of probe, Cable, Power chain</td>
<td></td>
</tr>
</tbody>
</table>

---

### Types of Uncertainty Sources

- **Power drift**: Measurement drift and body influence.
- **Body influence**: The influence of the body on the measurement.
- **Noise**: Random variations in the measurement.
- **Mechanical constraints**: Tripod positioning and mismatch between receiving antennas.
- **Spatial averaging**: Calibration and power receiver.
- **Isotropy/linearity**: Of the probe and cable.

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### Graphs

- **Uncertainty for Power Drift (dB)**: Showing the standard deviation and standard uncertainty.
- **Deviation between Different Distances (dB)**: Displaying data points for distances of 1m-2m, 1m-3m, and 2m-3m.
- **Mismatches**: Graph showing mismatches over time.

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The estimated uncertainty satisfy the recommendation by international standard (under 6 dB)

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical parameter</td>
<td>Power drift</td>
<td>Student-t</td>
<td>0.67</td>
<td>2.05</td>
<td>29</td>
<td>Small sample, unknown population mean &amp; variance</td>
<td>0.33</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Influence of body</td>
<td>Student-t</td>
<td>0.22</td>
<td>2.05</td>
<td>29</td>
<td>Small sample, unknown population mean &amp; variance</td>
<td>0.11</td>
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**Expanded uncertainty**

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<th>Uncertainty sources</th>
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<th>Uncertainty value [dB]</th>
<th>Divisor</th>
<th>DoF</th>
<th>Rationale of distribution</th>
<th>Standard uncertainty [dB]</th>
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Source: Byung Chan Kim et al., “Uncertainty Estimation for Evaluating of Human Exposure Levels to RF Electromagnetic Fields from Cellular Base Stations,” Accepted in IEEE Trans. on EMC and will publish soon.
Thank you and Questions?