Intercomparison of Calculated Incident Power Density and Temperature Rise for Exposure from Different Antennas at 10–90 GHz

Kun Li1,2, Member, IEEE, Yinliang Diao2, Member, IEEE, Kensuke Sasaki3, Member, IEEE, Alexander Prokop4, Member, IEEE, Dragan Poljak5, Senior Member, IEEE, Vicko Doric5, Member, IEEE, Jingtian Xi6, Member, IEEE, Sachiko Kodera7, Member, IEEE, Akimasa Hirata7, Fellow, IEEE, Walid El Hajji8, Member, IEEE.

1Faculty of Engineering and Design, Kagawa University, Takamatsu 761-0396, Japan
2College of Electronic Engineering, South China Agricultural University, Guangzhou 510642, China
3National Institute of Information and Communications Technology, Tokyo 184-8795, Japan
4Dassault Systèmes SIMULIA, Darmstadt, Germany
5University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, 21000 Split, Croatia
6Foundation for Research on Information Technologies in Society (IT\#IS), 8004, Zurich, Switzerland
7Department of Electrical and Mechanical Engineering, Nagoya Institute of Technology, Nagoya 466-8555, Japan
8Intel Corporation, Wireless RF Lab, Intel, Antibes 06600, France

Corresponding author: Kun Li (e-mail: li.kun@kagawa-u.ac.jp).

ABSTRACT Recently, international exposure guidelines/standards for human protection from electromagnetic fields were revised. For frequencies between 6-300 GHz, the permissible incident power density is defined as the reference level, which is derived from a new metric “absorbed/epithelial power density” based on thermal modeling. However, only a few groups computed the power density and the resultant temperature rise at frequencies greater than 6 GHz, where their exposure conditions were different. This study presents the first intercomparison study of the incident power density and the resultant temperature rise in a human body exposed to different frequency sources ranging from 10 to 90 GHz. This intercomparison aims to clarify the main causes of numerical calculation errors in dosimetry analyses through objective comparison of computation results from six organizations using their numerical methods with various body and antenna models. The intercomparison results indicate that the maximum relative standard deviation (RSD) of peak spatially averaged incident power densities for dipole and dipole array antennas is less than 22.1% and 6.3%, respectively. The maximum RSD of the heating factor, which is defined as the ratio of the peak temperature elevation at the skin surface to the peak spatially averaged incident power density in free space, for dipole and dipole array antennas is less than 43.2% and 41.2%, respectively. The deviations in the heating factors caused by different body models and dielectric/thermal parameters are within 33.1% and 19.6% at 10 and 30 GHz, respectively, when the antenna-to-skin model distance is greater than 5 mm. Under this condition (>5 mm), the deviation in the heating factors caused by different antenna models at 30 GHz does not exceed 26.3%. The fair agreement among the intercomparison results demonstrates that numerical calculation errors of dosimetry analyses caused by the definition of spatially averaged incident power density are marginal.

INDEX TERMS Millimeter wave exposure, Radiation safety, Standardization, Electromagnetic field, Dosimetry modeling, Skin model, Temperature rise, Incident power density

I. INTRODUCTION
Compliance assessment of electromagnetic field (EMF) emitted from wireless devices is one of the essential procedures to protect humans from excessive EMF exposure. However, the assessment of EMF is challenging due to the complexity of the electromagnetic field and the complexity of the human body. The International Commission on Non-Ionizing Radiation Safety (ICNIRP) has established guidelines for the exposure of humans to electromagnetic fields, which are based on the concept of reference levels. The reference levels are used to determine whether a particular exposure is safe or not. The reference levels are based on the biological effects of electromagnetic fields and are expressed in terms of the specific absorption rate (SAR) or the electric field strength. The SAR is defined as the ratio of the power absorbed by the body to the mass of the body. The electric field strength is defined as the magnitude of the electric field in the air around the body. The reference levels for the SAR and the electric field strength are expressed in terms of the frequency of the electromagnetic field. For example, the reference level for the SAR at 10 MHz is 0.8 W/kg, and the reference level for the electric field strength at 10 MHz is 10 V/m. The reference levels are revised periodically to account for new scientific findings.

Permission external exposure reference levels or internal basic restrictions have been prescribed in international exposure guidelines and standards, which are established by the International Commission on Non-Ionizing Radiation Safety (ICNIRP) and other national and international organizations. The ICNIRP guidelines are based on the concept of reference levels, which are expressed in terms of the specific absorption rate (SAR) or the electric field strength. The SAR is defined as the ratio of the power absorbed by the body to the mass of the body. The electric field strength is defined as the magnitude of the electric field in the air around the body. The reference levels for the SAR and the electric field strength are expressed in terms of the frequency of the electromagnetic field. For example, the reference level for the SAR at 10 MHz is 0.8 W/kg, and the reference level for the electric field strength at 10 MHz is 10 V/m. The reference levels are revised periodically to account for new scientific findings.

The ICNIRP guidelines are based on the concept of reference levels, which are expressed in terms of the specific absorption rate (SAR) or the electric field strength. The SAR is defined as the ratio of the power absorbed by the body to the mass of the body. The electric field strength is defined as the magnitude of the electric field in the air around the body. The reference levels for the SAR and the electric field strength are expressed in terms of the frequency of the electromagnetic field. For example, the reference level for the SAR at 10 MHz is 0.8 W/kg, and the reference level for the electric field strength at 10 MHz is 10 V/m. The reference levels are revised periodically to account for new scientific findings.

This work is licensed under a Creative Commons Attribution 4.0 License. For more information, see https://creativecommons.org/licenses/by/4.0/
Protection (ICNIRP) and IEEE International Committee on Electromagnetic Safety (ICES) Technical Committee (TC) 95.

International standards of products for compliance assessment have been established by International Electrotechnical Commission (IEC) TC106 and IEEE ICES TC34 based on the exposure guidelines and standards.

Two international exposure safety guidelines/standards, i.e., ICNIRP guidelines (100 kHz–300 GHz) [1] and IEEE ICES C95.1 standard [2], were revised in 2020 and 2019, respectively. One of the primary changes in the revised guidelines/standards is the introduction of a new exposure metric at frequencies greater than 6 GHz, where the absorbed/epithelial power density [3][4] was used as the basic restriction (BR) [1] or dosimetric reference limit (DRL) [2]. By contrast, the corresponding incident power density (IPD) in free space is derived using a thermal model (computation) as the reference level (hereafter called reference level (RL) for simplicity) [1] or exposure reference level (ERL) [2] conservatively. Based on the guidelines/standards [1][2], the IPD should be averaged over an area of 4 cm² for frequencies from 6 to 300 GHz. For frequencies higher than 30 GHz, additional criteria of IPD averaged over 1 cm² are given with a relaxation of RL/ERL by a factor of 2 for local beam-like exposures [1] [2]. RL and ERL are more practical metrics for evaluating dosimetric quantities than BR/DRL and are easier to conduct compliance assessments. Note that the IPD has been defined as BR in the previous versions of the guidelines/standards [5][6].

In the exposure guidelines/standards, the definition of the spatial average of IPD is theoretically defined. However, as product safety standards are being developed, one concern is how to define the spatial average of IPD at frequencies greater than 6 GHz while considering practical measurement procedures. The exposure guidelines are intended to prevent excessive temperature rise, so the effect of IPD definition and the averaging method on the temperature rise should also be considered [7]–[18].

With the progress in the development of product standards for compliance assessment, the importance of a more precise and unambiguous definition of the spatial average of IPD based on the correlation of that with temperature elevation became obvious in facilitating practical evaluation procedures. One aspect of this definition is related to the IPD quantity averaged over the prescribed surface area, which can be calculated using two methods:

- Only the components of IPD vectors normal to the averaging surface of the body are used for spatial averaging.
- The magnitudes (norms) of IPD vectors are averaged over the area, irrespective of the orientation.

A working group 5 under Subcommittee 6 of IEEE ICES TC95 has been established to clarify these aspects. Some recent studies have investigated these two IPD definitions by [19]–[26], including oblique incidence for near-field [27][28] and plane-wave exposure conditions [29]–[32]. However, in this emerging frequency range, a limited number of groups computed the power density and temperature rise in the human body models for EMF exposure above 6 GHz. The cause of numerical computation errors has not been objectively investigated by comparing different numerical methods and models. Such an intercomparison has been conducted for standardization, even in frequency bands of a few GHz [33]. Thus, the first mission of the working group was to perform an intercomparison of the IPD and the resultant temperature rise for dosimetry analysis at frequencies greater than 6 GHz.

This study computed the spatially averaged IPD and the peak temperature rise at the skin surface from 10 to 90 GHz using computational approaches. An intercomparison of numerical calculation errors from six research groups using their simulation codes and commercial EM solvers with various body and antenna models was performed.

II. Analytical Model and Method

A. Exposure Scenarios

Six different organizations collaborated to conduct this study: the National Institute of Information and Communications Technology (NICT), Nagoya Institute of Technology (NITech), South China Agricultural University (SCAU), Dassault Systèmes SIMULIA (3DS), Foundation for Research on Information Technologies in Society (IT’IS), and University of Split (UniSplit). Table I presents an overview of scenarios evaluated numerically by the participating organizations. The antenna models for numerical simulations, the simplified human body models, and the thermal parameters are described in Sections II-B, II-C, and II-D, respectively.

| TABLE I | EXPOSURE SCENARIOS |
|----------|---------------------|
| Antenna type | Frequency [GHz] | Distance [mm] | Organizations |
| Dipole | 10, 30, 60, 90 | 2, 5, 10, 50, 150 | NICT, NITech, SCAU, 3DS, UniSplit, IT’IS |
| Dipole Array | 10, 30, 60, 90 | 2, 5, 10, 50, 150 | NICT, NITech, SCAU |
| Patch Array | 30 | 2, 5, 10 | NICT, SCAU, 3DS |
| Slot Array | 30 | 2, 5, 10 | IT’IS, 3DS |

As presented in Table I, a separation distance between the antenna and the skin surface ranging from 2 to 150 mm was considered. The ICNIRP guidelines [1] state, “As a rough guide, distances > 2D/λ [m], between λ/2π and 2D/λ [m], and < λ/2π [m] from an antenna correspond approximately to the far-field, radiative near-field and reactive near-field, respectively, where D and λ refer to the longest dimension of
**the antenna and wavelength, respectively, in meters.**
Therefore, some exposure scenarios considered in this study may not be in the applicable range in IPD specified in the safety guidelines [1]. Nonetheless, results for all conditions will be presented in this study because our main purpose is to clarify the computational difference computed by different groups. The thickness of the chassis would be close to 2 mm, so the minimum distance was considered an extreme case. Note that in most wireless device use scenarios, the antenna is not located close to the body to such a separation distance.

**B. Computational Antenna Models**
The antenna models for numerical simulations used by different organizations are illustrated in Fig. 1. The following antenna models were suggested in the discussion of a working group 5 under Subcommittee 6 of IEEE ICES TC95. The same configurations are used even in this study. The total antenna input power was normalized to 10 mW in this study.

1) **Half-wavelength dipole antenna**
Fig. 1 (a) illustrates a half-wavelength dipole modeled as perfect electric conductor. Dipoles working at 10, 30, 60, and 90 GHz were designed. For most of organizations, the antenna was resonated with an adjusted length to obtain the maximum radiation power emitted from the antenna as possible. Table II summarizes the dipole length used by each organization.

2) **Dipole array antenna**
4-by-4 dipole antenna arrays working at frequencies of 10, 30, 60, and 90 GHz have been studied (see Fig. 1 (b)). The same length, as listed in Table II, was used by the corresponding organization for the dipole element in the array. The separation distance between the feeding points of any two adjacent dipole elements was \( \lambda / 2 \), where \( \lambda \) represents the free-space wavelength.

3) **Patch array antenna**
The dimension of a square patch array at 30 GHz is shown in Fig. 1 (c). The patch array has a 100 mm × 100 mm × 0.6 mm dielectric substrate with \( \varepsilon_r \) of 2.2. The length of the patch element is 0.3\( \lambda \) (i.e. 3 mm at 30 GHz), whereas the separation distance between adjacent patch elements is 0.5\( \lambda \) (i.e. 5 mm at 30 GHz).

4) **Slot array antenna**
A pyramidal horn loaded with a slot array operating at 30 GHz is shown in Fig. 1 (d). The slot array consisted of 6 × 7 rectangular slots symmetrically arranged on the horn aperture and was fabricated in a 0.15-mm-thick stainless steel sheet. The antenna is one of the standardized system validation sources specified in IEC/IEEE [34]–[36].

**C. Skin Models and Parameters**
Three stratified skin models were used in this study for dosimetry analysis. Variations in the inner tissue composition are illustrated in Fig. 2 (a). The dimensions of the skin models are \( L \times L \times T \) (mm\(^3\)), as illustrated in Fig. 2 (b), and are summarized in Table III. The dielectric properties of tissues obtained by a four-Cole–Cole dispersion model [37]–[39] were used, except for the four-layer skin model [40]–[42], which used independent measurement data. The thicknesses and thermal properties of each tissue layer in the human block models are summarized in Table IV.

![Figure 1](imageURL)

![Figure 2](imageURL)

**TABLE II**

| Org. | 10 GHz [mm] | 30 GHz [mm] | 60 GHz [mm] | 90 GHz [mm] |
|------|-------------|-------------|-------------|-------------|
| O1   | 13.6        | 4.4         | 2.2         | N/A         |
| O2   | 13.5        | 4.25        | 2.125       | 1.3         |
| O3   | 13.5        | 4.75        | 2.375       | 1.5         |
| O4   | 15.0        | 5.0         | 2.5         | N/A         |
| O5   | 13.6        | 4.53        | 2.27        | 1.51        |
| O6   | 15.0        | 5.0         | 2.5         | 1.67        |

Abbreviations: Organization (Org.).
D. Computation of Electromagnetic Field

Several numerical techniques have been used to evaluate the IPD in free space and the specific absorption rate (SAR) inside the simplified human block models. Specifically, the finite-difference time-domain (FDTD) method has been adopted by four organizations [43], whereas the finite integration technique (FIT) [44] and the Galerkin-Bubnov indirect boundary element method (GB-IBEM) [45] have been used separately by the two other organizations. Depending on the adopted numerical techniques, different boundary conditions (BCs) have been used to truncate the computational domain. Perfect matched layers have been used as absorbing BCs to suppress (or minimize) reflections of EMF at the boundaries of the computational domain. The numerical methods and spatial resolution in simulations are summarized in Table V.

### TABLE III
**DIMENSION OF SKIN MODELS FOR EACH ORGANIZATION**

| Org. | Dimension | 10 GHz | 30 GHz | 60 GHz | 90 GHz |
|------|-----------|--------|--------|--------|--------|
| O1   | L [mm]    | 100    | 100    | 50     | N/A    |
|      | T [mm]    | 20     | 20     | 20     | N/A    |
| O2   | L [mm]    | 400    | 200    | 100    | 80     |
|      | T [mm]    | 30     | 30     | 30     | 30     |
| O3   | L [mm]    | 100    | 50     | 50     | 50     |
|      | T [mm]    | 20     | 20     | 20     | 20     |
| O4   | L [mm]    | 200    | 150    | 80     | N/A    |
|      | T [mm]    | 100    | 50     | 40     | N/A    |
| O5   | L [mm]    | 200    | 150    | 100    | 60     |
|      | T [mm]    | 100    | 75     | 50     | 30     |

### TABLE IV
**Tissue thicknesses (T) and thermal properties using different skin models by each organization**

| Org. | Tissue  | Thic. [mm] | k [W/(m°C)] | B [W/(m²°C)] | ρ [kg/m³] |
|------|---------|------------|-------------|--------------|-----------|
| O1   | Epi-dermis | 0.2        | 0.45        | 0            | 1.109     |
|      | Dermis  | 1.0        | 0.42        | 9,100        | 1.109     |
|      | Fat     | 3.8        | 0.25        | 1,700        | 911       |
|      | Muscle  | 15.0       | 0.5         | 2,700        | 1,090     |
| O2   | Skin    | 2          | 0.42        | 7,441        | 1,125     |
|      | Fat     | 12         | 0.25        | 1,903        | 916       |
|      | Muscle  | 16         | 0.5         | 2,691        | 1,047     |
| O3   | Skin    | 1.5        | 0.37        | 7,441        | 1,109     |
|      | Fat     | 4          | 0.21        | 1,903        | 911       |
|      | Muscle  | 14.5       | 0.49        | 2,691        | 1,090     |
| O4   | Skin    | T4(1)     | 0.293       | 9,100        | 1,100     |
|      | O5      | Skin      | T6(2)      | 0.37        | 2,230     | 1,100     |
|      | O6      | Skin      | 1.5        | 0.42        | 9,100     | 1,109     |
|      | Fat     | 4          | 0.25        | 1,700        | 911       |
|      | Muscle  | 14.5       | 0.5         | 2,700        | 1,090     |

**Abbreviations:** Thickness (Thic.);

| O1   | O2   | O3   | O4   | O5   | O6   |
|------|------|------|------|------|------|
| FDTD | FDTD | FDTD | FDTD | FDTD | FDTD |
| 0.2  | 0.2  | 0.2  | 0.2  | 0.2  | 0.2  |
| 0.5  | 0.5  | 0.5  | 0.5  | 0.5  | 0.5  |
| 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 |
| 0.25 | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 |

**Abbreviations:** Resolution (Res.).

Each organization performed two separate EM calculations for each modeling scenario. First, the IPD in free space was calculated without the presence of the body. Then, the simplified human block model was introduced (Section II-C), and electric field strengths in tissue were calculated. In this latter case, the SAR, which is the input parameter for
evaluating temperature increase, has been calculated using the well-known expression of Eq. (1):

$$\text{SAR}(r) = \frac{\sigma(r)}{2\rho(r)} |E(r)|^2,$$

(1)

where $\sigma$ represents the tissue conductivity (S/m), and $\rho$, the mass density (kg/m$^3$). $r$ denotes the position vector, and $E$ denotes the complex electric field inside the body.

### E. Thermal Computation

Thermal calculations have been performed to obtain the time-varying tissue temperature ($T$) by solving the Pennes Bio-Heat Equation (PBHE) [46]–[51], as expressed by Eq. (2):

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

(2)

where $T$ and $T_b$ represent temperatures of human tissues and blood (°C), respectively. $\kappa$ and $c$ represent the thermal conductivity (W/(m K)) and heat capacity (J/(kg K)), respectively. $A$ and $B$ denote the basal metabolism per unit volume (W/m$^3$) and a term associated with blood flow (W/(m$^3$ K)), respectively.

At a steady state, the temperature elevation ($\Delta T$) can be solved using Eq. (3):

$$0 = \nabla \cdot [\kappa(r) \cdot \nabla \Delta T(r)] + \rho(r)\text{SAR}(r) - B(r,t)\Delta T(r).$$

(3)

Note that the coefficient representing the basal metabolism of the body does not affect the temperature increase caused by EMF exposure when thermoregulatory responses are ignored, as considered in this study. The boundary condition for PBHE describing the heat exchange between air and the skin tissue is given by Eq. (4):

$$-\kappa(r) \frac{\partial T(r,t)}{\partial n} = h \times [T_{\text{surf}}(r,t) - T_{\text{air}}(t)],$$

(4)

where $h$, $T_{\text{surf}}$, and $T_{\text{air}}$ denote the heat transfer coefficient (W/(m$^2$ K)), the surface temperature of the tissue (°C), and air temperature (°C), respectively, and $n$ represents the normal vector component at the boundary surface. Instead, adiabatic BCs were assigned to all inner boundaries, which are given by the following equation:

$$\frac{\partial T(r,t)}{\partial n} = 0.$$ 

(5)

### F. Metrics and Post-processing Methods

In this study, two definitions of the spatial-average power density ($s\text{PD}$) for the EMF were examined in the absence of the human body. The first is the spatial average of the normal component of the time-averaged PD, as defined by Eq. (5).

The second is the spatial average of the norm of the time-averaged PD, as defined by Eq. (6), which considers all three components of the Poynting vector.

$$s\text{PD}_n = \frac{1}{2\pi} \int_{A} \text{Re}[E \times H^*] \cdot ndA$$

(5)

$$s\text{PD}_{tot} = \frac{1}{2\pi} \int_{A} \|\text{Re}[E \times H^*]\|dA$$

(6)

$E$ and $H$ denote the complex electric field and magnetic field vectors, respectively; * denotes the complex conjugate; $A$ represents the averaging area; and $n$ represents the unit vector normal to the evaluation plane. Then, the heating factor ($HF$), which is defined as the ratio of the peak steady-state temperature rise ($p\Delta T$) at the skin surface calculated using the assumed thermal parameters to the peak spatial-average PD ($p\text{PD}$) [14], was computed using Eq. (7):

$$HF = \frac{p\Delta T}{p\text{PD}}.$$ 

(7)

The corresponding definitions of $HF$s hereafter are denoted as $HF_n (p\Delta T/p\text{PD}_n)$ and $HF_{tot} (p\Delta T/p\text{PD}_{tot}).$

### III. Intercomparison Results

This section presents the intercomparison results in terms of peak spatial-average IPD and $HF$s using different antennas. The intercomparison plots of $p\text{PD}_n$ and $p\text{PD}_{tot}$, as well as $HF_n$ and $HF_{tot}$, were averaged over an area of $A = 4$ cm$^2$ at 6–30 GHz and $A = 1$ cm$^2$ above 30 GHz. The antenna-to-skin separation distance varied from 2 to 150 mm.

### A. Comparison of Peak Spatial-Average Incident Power Density

Figures 4 and 5 show the intercomparison results of $p\text{PD}$ as a function of the antenna-to-skin separation distance $d$ exposed to the single dipole and the 4 × 4 dipole array antenna for the exposure scenarios in Table I, respectively, at a frequency from 10 to 90 GHz. The lines with solid markers indicate the results of $p\text{PD}_n$, whereas the dashed lines with empty markers denote the results of $p\text{PD}_{tot}$.

In Fig. 4, both $p\text{PD}_n$ and $p\text{PD}_{tot}$ decrease monotonically with an increase in the separation distance $d$. $p\text{PD}_{tot}$ is greater than $p\text{PD}_n$ in the 2–150 mm range. In the 2–5 mm range, an obvious difference between $p\text{PD}_n$ and $p\text{PD}_{tot}$ is observed, where the maximum absolute difference between $p\text{PD}_n$ and $p\text{PD}_{tot}$ is up to 3.8 dB at 10 GHz when $d = 2$ mm. At $d > 5$ mm, however, the corresponding difference decreases to less than 1 dB and approaches 0 dB when $d$ increases above 50 mm, which is in the far-field region of a half-wavelength dipole antenna.

By contrast, when the 4 × 4 dipole array is used as an exposure source, as illustrated in Fig. 5, owing to the dispersion of multiple near-field peaks caused by the wave
source of the antenna array, the trends of psPDs completely differ from those of the dipoles illustrated in Fig. 4. In addition, the absolute difference between psPD$_n$ and psPD$_{tot}$ is significantly reduced for cases of the 4 × 4 dipole array; the maximum absolute difference at $d = 2$ mm is reduced to less than 1.5 dB at 10 GHz, and it is not greater than 0.1 dB when $d$ is greater than 5 mm. The above results indicate that at a separation distance $d > 5$ mm, there is no obvious discrepancy between psPD$_n$ and psPD$_{tot}$ for either case of dipole or dipole array source.

Tables VI and VII present the statistical mean value and standard deviation of psPD$_n$ and psPD$_{tot}$ of the numerical results from the six organizations for cases of the dipole and dipole array, respectively. The separation distances from the antenna for cases at $d = 2$, 5, and 10 mm were compared. Hereafter, we evaluate the relative standard deviation (RSD), which is defined as the ratio of standard deviation to the mean value, as a metric for intercomparison of different research groups.

| Frequency [GHz] | Peak Spatial-Average IPD $d = 2$ mm | $d = 5$ mm | $d = 10$ mm |
|-----------------|------------------------------------|------------|-------------|
| 10              | 11.13 ± 0.85                       | 8.43 ± 0.25| 5.28 ± 0.05 |
| 30              | 11.01 ± 0.46                       | 8.56 ± 0.14| 5.48 ± 0.06 |
| 60              | 37.19 ± 0.94                       | 21.84 ± 0.35| 9.49 ± 0.15 |
| 90              | 37.48 ± 1.23                       | 22.09 ± 0.63| 9.6 ± 0.26  |
| 10              | 21.19 ± 4.68                       | 11.81 ± 0.95| 6.24 ± 0.16 |
| 30              | 20.6 ± 1.04                        | 12.2 ± 0.27| 6.55 ± 0.07 |
| 60              | 56.93 ± 1.54                       | 26.13 ± 0.39| 10.14 ± 0.16|
| 90              | 57.85 ± 1.83                       | 26.44 ± 0.51| 10.26 ± 0.26|

| Frequency [GHz] | Peak Spatial-Average IPD $d = 2$ mm | $d = 5$ mm | $d = 10$ mm |
|-----------------|------------------------------------|------------|-------------|
| 10              | 2.12 ± 0.01                        | 1.87 ± 0.004| 1.82 ± 0.01 |
| 30              | 12.01 ± 0.25                       | 11.06 ± 0.26| 9.73 ± 0.11 |
| 60              | 45.46 ± 1.18                       | 38.25 ± 0.76| 35.57 ± 1.16|
| 90              | 50.53 ± 3.17                       | 44.07 ± 2.27| 39.21 ± 0.35|
| 10              | 2.9 ± 0.06                         | 1.95 ± 0.01| 1.85 ± 0.01 |
| 30              | 12.48 ± 0.13                       | 11.48 ± 0.25| 9.81 ± 0.08 |
| 60              | 46.87 ± 1.29                       | 38.78 ± 0.57| 35.76 ± 1.19|
| 90              | 53.47 ± 2.85                       | 44.91 ± 2.61| 39.73 ± 0.67|

FIGURE 4. Spatially averaged incident power densities as functions of the antenna-to-skin separation distance using half-wavelength dipoles at frequencies of (a) 10 GHz, (b) 30 GHz, (c) 60 GHz, and (d) 90 GHz.

FIGURE 5. Spatially averaged incident power densities as functions of the antenna-to-skin separation distance using 4 × 4 dipole arrays at frequencies of (a) 10 GHz, (b) 30 GHz, (c) 60 GHz, and (d) 90 GHz.
For the case of the dipole source, as presented in Table VI, the maximum RSD of $\psi$S$^D_pD_n$ and $\psi$S$^PD_n$ is 7.6% and 22.1%, respectively, at the frequency of 10 GHz when $d = 2$ mm. At $d > 5$ mm, the RSD of $\psi$S$^D_pD_n$ and $\psi$S$^PD_n$ is less than 3% and 8.1% and does not exceed 1.0% and 2.6%, respectively, when the separation distance $d$ increases to 10 mm.

By contrast, for the case of the $4 \times 4$ dipole array, as presented in Table VII, the maximum RSD is nonexistent at 10 GHz when $d = 2$ mm. For both cases of $\psi$S$^D_pD_n$ and $\psi$S$^PD_n$, the maximum RSD is approximately 6.3% ($d = 2$ mm) and 5.8% ($d = 5$ mm), respectively, at the frequency of 90 GHz. The maximum RSD of the dipole arrays decreases significantly compared to that of the dipole sources. When $d$ increases to 10 mm, the corresponding maximum RSD for each $\psi$S$^D_pD_n$ and $\psi$S$^PD_n$ is less than 3.3%.

**TABLE VIII**

| Heating factors | Frequency [GHz] | $d = 2$ mm | $d = 5$ mm | $d = 10$ mm |
|-----------------|-----------------|------------|------------|-------------|
| $HF_n$ ['C/W/m²'] | 10 | 0.0632 ± 0.0021 | 0.0147 ± 0.0062 | 0.0061 ± 0.0024 |
| $HF_{tot}$ ['C/W/m²'] | 30 | 0.0447 ± 0.0019 | 0.0213 ± 0.0054 | 0.0131 ± 0.0033 |
| | 60 | 0.0142 ± 0.0033 | 0.0102 ± 0.0027 | 0.0092 ± 0.0024 |
| | 90 | 0.0233 ± 0.0059 | 0.0125 ± 0.0031 | 0.0113 ± 0.0021 |
| $HF_{tot}$ ['C/W/m²'] | 10 | 0.0118 ± 0.0011 | 0.0046 ± 0.0021 | 0.0065 ± 0.0020 |
| | 30 | 0.0149 ± 0.0010 | 0.0085 ± 0.0037 | 0.0092 ± 0.0028 |
| | 60 | 0.0085 ± 0.0021 | 0.0085 ± 0.0023 | 0.0086 ± 0.0022 |
| | 90 | 0.0104 ± 0.0039 | 0.0025 ± 0.0019 | 0.0105 ± 0.0019 |

**TABLE IX**

| Heating factors | Frequency [GHz] | $d = 2$ mm | $d = 5$ mm | $d = 10$ mm |
|-----------------|-----------------|------------|------------|-------------|
| $HF_n$ ['C/W/m²'] | 10 | 0.0028 ± 0.0003 | 0.005 ± 0.0012 | 0.0042 ± 0.0017 |
| | 30 | 0.006 ± 0.0007 | 0.0265 ± 0.003 | 0.0221 ± 0.0034 |
| | 60 | 0.0077 ± 0.0001 | 0.0167 ± 0.0001 | 0.0138 ± 0.0046 |
| | 90 | 0.0192 ± 0.0006 | 0.0257 ± 0.0004 | 0.0183 ± 0.0014 |
| $HF_{tot}$ ['C/W/m²'] | 10 | 0.0153 ± 0.0021 | 0.0048 ± 0.0012 | 0.0041 ± 0.0017 |
| | 30 | 0.0057 ± 0.0006 | 0.0235 ± 0.0029 | 0.0219 ± 0.0033 |
| | 60 | 0.0074 ± 0.0001 | 0.0165 ± 0.0002 | 0.0137 ± 0.0046 |
| | 90 | 0.0181 ± 0.0055 | 0.0252 ± 0.0046 | 0.0181 ± 0.0016 |

**FIGURE 6.** Heating factors of $\psi$S$^D_pD_n$ and $\psi$S$^PD_n$ as functions of the antenna-to-skin separation distance using half-wavelength dipoles at frequencies of (a) 10 GHz, (b) 30 GHz, (c) 60 GHz, and (d) 90 GHz.

**FIGURE 7.** Heating factors of $\psi$S$^D_pD_n$ and $\psi$S$^PD_n$ as functions of the antenna-to-skin separation distance using $4 \times 4$ dipole arrays at frequencies of (a) 10 GHz, (b) 30 GHz, (c) 60 GHz, and (d) 90 GHz.
The above results indicate that for the EMF calculation in the antenna near-field, such as the extreme case of \( d = 2 \) mm, there will be noticeable differences in the results from the different organizations, especially for cases of \( pSPD_n \). At a separation distance \( d > 5 \) mm, however, the difference in both \( pSPD_n \) and \( pSPD_{tot} \) for all cases of the dipole and dipole array is less than 8.1%. When one considers the different numerical methods used by each organization, this difference is relatively small.

**B. Comparison of Heating Factors**

Figures 6 and 7 show the intercomparison results of the \( HF_s \) as functions of the antenna-to-skin separation distance \( d \) exposed to the radiation sources of the dipole and the \( 4 \times 4 \) dipole array, respectively. In Figs. 6 and 7, the lines with solid markers indicate the results of \( HF_n \), whereas the dashed lines with empty markers denote those of \( HF_{tot} \).

In Fig. 6, at frequencies of 10 and 30 GHz when \( d = 2 \) mm, a significant increase in \( HF_s \) is observed. As \( d \) increases to 10 mm, the profiles of \( HF_n \) and \( HF_{tot} \) at 10 and 30 GHz decrease gradually. By contrast, the results of \( HF_s \) at 60 and 90 GHz show a relatively gentle trend of variation from 2 to 150 mm. By contrast, the deviation between \( HF_n \) and \( HF_{tot} \) in the range of 2 to 5 mm is up to 58% (3.8 dB) at 10 GHz. At \( d > 5 \) mm, the difference decreases to less than 20% (1 dB), and almost no difference is observed when \( d \) increases above 50 mm, corresponding to the results mentioned in Section III-A.

When the \( 4 \times 4 \) dipole array is used, as shown in Fig. 7, the entire difference between \( HF_n \) and \( HF_{tot} \) decreases significantly compared to the dipole source shown in Fig. 6, owing to the dispersion of the near-field distribution of the dipole array. The maximum difference between \( HF_n \) and \( HF_{tot} \) at \( d = 2 \) mm is less than 29% (1.5 dB) and does not exceed 2% (0.1 dB) when \( d \) is greater than 5 mm.

---

**FIGURE 8.** Distributions of spatially averaged incident power densities and surface temperature elevation for dipole and dipole array antennas at 30 GHz with antenna-skin separation distance of 2, 5, and 10 mm from different organizations: (a) dipole, (b) dipole array.
Fig. 8 shows the distributions of $sPD_a$, $sPD_{tot}$ and $\Delta T$ for dipole and dipole array antenna at 30 GHz when $d$ is 2, 5, and 10 mm. The area for spatial average of IPD were set to 1 and 4 cm$^2$, respectively. For simplicity, we have selected the results of the first three organizations (O1, O2, and O3) that provided all the data of dipole and dipole array, as shown in Figs. 8 (a) and (b), respectively. In Fig. 8, for each research organization, the distributions of using dipole array antennas show higher locality compared to those of using single dipoles. When the antenna-skin separation distance $d$ is larger than 2 mm, there is no large obvious difference in the distributions between the two definitions of IPD.

Tables VIII and IX list the statistical mean values and standard deviations of the $HF_n$ and $HF_{tot}$ of the numerical results from the six organizations for cases of the dipole and the dipole array, respectively. For the case of the dipole source, as presented in Table VIII, the maximum RSD of $HF_n$ and $HF_{tot}$ is 42.5% and 43.2%, which occurred at frequencies of 30 GHz when $d = 2$ mm and 10 GHz when $d = 5$ mm, respectively. The corresponding maximum RSD is less than 38.7% and 39%, respectively, when $d = 10$ mm.

For the case of the $4 \times 4$ dipole array, as presented in Table IX, the maximum RSD of $HF_n$ and $HF_{tot}$ decreases to approximately 31% and 30%, respectively, at a frequency of 90 GHz when $d = 2$ mm. At $d = 5$ mm, the corresponding RSD of $HF_n$ and $HF_{tot}$ further decreases to less than 25% and 24.5%, respectively, at a frequency of 10 GHz but increases up to 41.2% for both $HF_n$ and $HF_{tot}$ at 10 GHz when $d$ increases to 10 mm.

The above results indicate that there is no obvious difference between $HF_n$ and $HF_{tot}$ when the antenna-to-model separation distance is greater than 5 mm. However, the difference in $HF_s$ from six organizations is relatively greater than that in $sPD$, indicating that a difference in the numerical analysis of temperature rise among various organizations may exist, as different skin models have been used.

C. Variability of Body Model and Thermal Parameter

Several body models with different tissue compositions were used in the working group’s intercomparison study. A previous study examined variabilities related to tissue thickness in a multi-layer model using the Monte Carlo method [41]. In this section, the variability in the calculated $HF_s$ caused by different body models and thermal parameters is further assessed. To avoid the discrepancies caused by the numerical methods, the computation is performed by organization 2 using the dipole source at frequencies of 10 and 30 GHz with their original code based on the following conditions:

- the same resolution and model structure,
- the same dielectric and thermal parameters,
- distance between the antenna and the model $d = 10$ mm, and
- the same antenna length: 13.25–13.5 mm (10 GHz) and 4.1–4.25 mm (30 GHz).

Note that the antenna length was adjusted in consideration of the difference in resolution used by each organization. The comparisons of $HF_s$ between organization 2 and other organizations are summarized in Table X for 10 GHz and Table XI for 30 GHz, respectively. As presented in Tables X and XI, the maximum difference observed at 10 and 30 GHz is 33.1% and 19.6%, respectively, compared to those of organization 2. The corresponding difference with other organizations is less than 12.7% and 17.6%, respectively. The global differences can be considered acceptable, indicating that the deviation for dosimetry analysis caused by the difference in body models and dielectric/thermal parameters is insignificant.

D. Variability of Antenna Model

The variations in RSD between different organizations in previous sections indicate that the $HF$ may be affected by the antennas used. In this section, the variability caused by the antenna models was investigated.

| TABLE X |
|---------------------------------------|
| **DIFFERENCE IN HEATING FACTORS DUE TO DIFFERENT MODELS AND THEIR DIELECTRIC/Thermal PARAMETERS USING HALF-WAVELENGTH Dipoles** |
| **AT 10 GHz REPLICATED BY ORGANIZATION 2** |
| **Org.** | $HF_n$ avg.1 | $HF_{tot}$ avg.1 | $HF_n$ avg.4 | $HF_{tot}$ avg.4 |
| O1 | -12.6% | -12.2% | -12.7% | -12.1% |
| O2 (ref.) | - | - | - | - |
| O3 | -10.9% | -10.1% | -10.8% | -8.2% |
| O4 | -4.5% | -4.3% | -6.2% | -5.4% |
| O5 | 0.0% | 0.8% | -0.3% | 1.3% |
| O6 | -30.0% | -31.3% | -30.9% | -33.1% |

| TABLE XI |
|---------------------------------------|
| **DIFFERENCE IN HEATING FACTORS DUE TO DIFFERENT MODELS AND THEIR DIELECTRIC/Thermal PARAMETERS USING HALF-WAVELENGTH Dipoles** |
| **AT 30 GHz REPLICATED BY ORGANIZATION 2** |
| **Org.** | $HF_n$ avg.1 | $HF_{tot}$ avg.1 | $HF_n$ avg.4 | $HF_{tot}$ avg.4 |
| O1 | 16.6% | 17.1% | 16.8% | 17.6% |
| O2 (ref.) | - | - | - | - |
| O3 | -14.7% | -14.0% | -14.7% | -12.4% |
| O4 | 4.9% | 5.0% | 3.7% | 3.9% |
| O5 | 8.6% | 9.3% | 8.3% | 9.2% |
| O6 | 18.9% | 19.6% | 18.7% | 19.4% |

Fig. 9 shows the $HF_s$ of $sPD$ using the antenna models, namely half-wavelength dipole, the $4 \times 4$ dipole array, the $4 \times 4$ patch array, and the pyramidal horn with a $6 \times 7$ slot array at 30 GHz, as illustrated in Fig. 1 (d). The spatial averaging area was set to $A = 4$ cm$^2$. The results at the separation distance of $d = 2$, 5, and 10 mm were compared. The error bars show the statistical mean value and the standard deviation of $HF_s$ from different organizations. The results of $HF_n$ and $HF_{tot}$ are illustrated in Figs. 9 (a) and (b), respectively.
As illustrated in Fig. 9, for each antenna model, except for the dipole array, the standard deviations increase markedly at \(d = 2\) mm compared with those at other separation distances. In Fig. 9 (a), the maximum RSD of HF\(_\text{r}\) is 42.5\%, 11.4\%, 32.7\%, and 58.6\% for the case of the dipole, dipole array, patch array, and slot array, respectively, when \(d = 2\) mm. The corresponding RSD of HF\(_\text{tot}\) is 42.6\%, 11\%, 31.7\%, and 60.3\%, respectively, as illustrated in Fig. 9 (b). At \(d = 5\) mm, the maximum RSD decreases to less than 26.3\% and does not exceed 25.5\% at \(d = 10\) mm, indicating a fair agreement across the different sets of results when \(d\) is greater than 5 mm. The overall level of deviation of HFs due to different antenna models at 30 GHz is comparable with those mentioned in Section III-B, demonstrating a slight dependency of the antenna model for numerical computation errors in the dosimetry analysis. The relatively large RSD for the case of the slot array can be attributed to the fact that only two organizations provided related results for intercomparison in this case, which may result in an increase in deviation due to the insufficient data for statistical analysis.

![FIGURE 9. Heating factors of sPD, and sPDtot using different antennas at 30 GHz with an averaging area of A = 4 cm²: (a) HF; (b) HFtot.](image)

IV. Discussion and Conclusion

As mentioned above, we establish exposure scenarios considering product safety in which a worst-case exposure is assumed and exposure guidelines/standards in which more practical consideration is included. In exposure guidelines/standards, some practical consideration is given. IEEE C95.1-2019 states that “the safety limits for electrostimulation are based on conservative assumptions of exposure; however, they cannot address every conceivable assumption.” Thus, our approximation is still useful for providing general intercomparison and interpreting the results. For a distance less than 5 mm, a potential application would be a body-worn wireless device. In such cases, the antenna would be supported by the metallic plate to avoid the interaction and maintain the antenna impedance. The misuse (e.g., incorrect orientation) of the antenna would be considered for product safety in general, rather than the EMF safety. Note that, in general, the output power of wearable devices would be sufficiently small, and the antenna type might be different from those considered in this study.

In exposure scenarios, especially for an antenna-to-model separation distance less than 5 mm, some hotspots were observed only beneath the antenna feeding point for dipole or dipole array antennas. The size of the focal area is comparable to the separation between two linear conductors, depending on the modeling of the feeding point. Note that this is not caused by the beam formation of multiple antennas or antenna arrays. When an antenna array was considered, the number of such focal points coincided with that of antenna elements, and the increase in the HF was thus insignificant when the separation between array elements was considered.

This study made the first intercomparison of calculated spatially averaged IPD and resultant temperature rise in a simplified body model for exposure from different antennas ranging from 10 to 90 GHz. The main causes of numerical calculation errors in the dosimetry analysis using various skin and antenna models were investigated using objective comparison of analysis results from six different research groups. The intercomparison results indicate that the maximum RSD of spatially averaged incident power densities is less than 22.1\% and 6.3\% for the dipole antenna and the dipole array, respectively. In addition, the maximum RSD of the HF, which is defined as the ratio of peak temperature elevation at the skin surface to peak spatially averaged IPD, does not exceed 43.2\% and 41.2\% for cases of the dipole antenna and the dipole array, respectively. Although there is a slight dependency on the body model, thermal parameters, and antenna models, the deviation of HFs is insignificant when one considers the numerical methods used by different organizations. The fair agreement among the intercomparison results demonstrates that numerical calculation errors of dosimetry analysis caused by the definition of spatially averaged IPD are marginal. By contrast, some other factors, such as the antenna type, the separation distance between the antenna and the body model, and the numerical method, may result in relatively large discrepancies.

REFERENCES

[1] ICNIRP, “Guidelines for Limiting Exposure to Electromagnetic Fields (100 kHz to 300 GHz),” Health Phys., vol. 118, no. 5, pp. 483–524, 2020.

[2] IEEE-C95.1, IEEE Standard for Safety Levels with Respect to Human Exposure to Electric, Magnetic and Electromagnetic Fields, 0 Hz to 300 GHz, NY, USA, 2019.

[3] Y. Diao, E. A. Rashed, and A. Hirata, “Assessment of absorbed power density and temperature rise for nonplanar body model under electromagnetic exposure above 6 GHz,” Phys. Med. Biol., vol. 65, no. 22, pp. 224001, Nov. 2020.
B. Thors, D. Colombi, Z. Ying, T. Bolin, and C. Törnevik, “Exposure to RF EMF from array antennas in 5G mobile communication equipment,” *IEEE Access*, vol. 4, pp. 7469–7478, Aug. 2016.

E. Carrasco, D. Colombi, K. R. Foster, M. C. Ziskin, and Q. Balzano, “Exposure Assessment of Portable Wireless Devices above 6 GHz,” *Radiation Protection Dosimetry*, vol. 183, no. 4, pp. 489–496, Jun. 2019.

D. Funahashi, T. Ito, A. Hirata, T. Iyama, and T. Onishi, “Averaging area of incident power density for human exposure from patch antenna arrays,” *JEICE Trans. Electron.*, vol. E101-C, no. 8, pp. 644–646, Aug. 2018.

T. Nakae, D. Funahashi, J. Higashiyama, T. Onishi, and A. Hirata, “Skin Temperature Elevation for Incident Power Densities From Dipole Arrays at 28 GHz,” *IEEE Access*, vol. 8, pp. 20663–20671, Jan. 2020.

Y. Diao, K. Li, K. Sasaki, K. Sachiko, I. Laakso, W. E. Haji, and A. Hirata, “Effect of Incidence Angle on the Incident Power Density Definition to Correlate Skin Temperature Rise for Millimeter Wave Exposures,” *IEEE Trans. Electromagn. Compat.*, vol. 63, no. 5, pp. 1709–1716, Oct. 2021.

K. Li, K. Sasaki, S. Watanabe, and H. Shirai, “Relationship between power density and surface temperature elevation for human skin exposure to electromagnetic waves with oblique incidence angle from 6 GHz to 1 THz,” *Phys. Med. Biol.*, vol. 64, no. 6, pp. 065016, Mar. 2019.

T. Samaras, N. Kuster, “Theoretical evaluation of the power transmitted to the body as a function of angle of incidence and polarization at frequencies> 6 GHz and its relevance for human body model validation,” *Bioelectromagnetics*, vol. 40, no. 2, pp. 136–139, Jan. 2019.

A. Hirata, S. Watanabe, O. Fujiwara, M. Kojima, K. Sasaki, and T. Shiozawa, “Temperature elevation in the eye of anatomically based human head models for plane-wave exposure,” *Phys. Med. Biol.*, vol. 52, no. 21, pp. 6389–6399, Oct. 2007.

T. Wu, T. S. Rappaport, and C. M. Collins, “Safe for generations to come: Considerations of safety for millimeter waves in wireless communications,” *IEEE Microw. Mag.*, vol. 16, no. 2, pp. 65–84, Mar. 2015.

B.B. Beard, et al., “Comparisons of computed mobile phone induced SAR in the SAM phantom to that in anatomically correct models of the human head” *IEEE Trans. Electromagn. Compat.*, vol. 48, no. 2, pp. 397–407, Jun. 2006.

S. Pfeiffer, E. Carrasco, P. Crespo-Valero, E. Neufeld, S. Kuhn, T. Samaras, A. Christ, M. H. Capstick, and N. Kuster, “Total Field Reconstruction in the Near Field Using Pseudo-Vector E-Field Measurements”, *IEEE Trans. Electromagn. Compat.*, vol. 61, no. 2, pp. 476–486, Apr. 2019.

Measurement Procedure for the Evaluation of Power Density Related to Human Exposure to Radio Frequency Fields From Wireless Communication Devices Operating Between 6 GHz and 100 GHz,” IEC TR 63170 ED1, 2018.

Assessment of power density of human exposure to radio frequency fields from wireless devices in close proximity to the head and body (Frequency range of 6 GHz to 300 GHz), IEC/IEEE document 63195-1 CDV, 2020.

S. Gabriel, R. W. Lau, and C. Gabriel, “The dielectric properties of biological tissues: III. Parametric models for the dielectric spectrum of tissues”, *Phys. Med. Biol.*, vol. 41, no. 11, pp. 2271–2293, Nov. 1996.

C. Gabriel, “Compilation of the dielectric properties of body tissues at RF and microwave frequencies,” Technical Report N.A/EO-TR-1996-0037, Occupational and Environmental Health Directorate Radiofrequency Radiation Division, Brooks Air Force Base, Texas, 1996.

P. A. Hasgall, et al., IT’IS Database for thermal and electromagnetic parameters of biological tissues, version 4.0, May 15, 2018. http://www.itis.ethz.ch/database

K. Sasaki, K. Wake, and S. Watanabe, “Measurement of the dielectric properties of the epidermis and dermis at frequencies from 0.5 GHz to 110 GHz,” *Phys. Med. Biol.*, vol. 59, no. 16, pp. 4739–4747, 2014.

K. Sasaki, M. Mizuno, and K. Wake, “Monte Carlo simulations of skin exposure to electromagnetic field from 10 GHz to 1 THz” Monte
Carlo simulations of skin exposure to electromagnetic field from 10 GHz to 1 THz,” *Phys. Med. Biol.*, vol. 62, pp. 6993–7010, 2017.

[42] K. Sasaki, K. Kawabata, Y. Shimizu, S. Watanabe, K. Wake, R. Suga, O. Hashimoto, “Design of a Skin Equivalent Phantom for Estimating Surface Temperature Elevation Due to Human Exposure to Electromagnetic Fields From 10 to 100 GHz,” *IEEE Trans. Electromagn. Compat.*, vol. 63, no. 5, pp. 1631–1639, Oct. 2021.

[43] A. Taflove and S. C. Hagness, *Computational Electrodynamics: The Finite-Difference Time-Domain Method*, Third Edit. ARTECH HOUSE, 2005.

[44] T. Weiland, “A Discretization Method for the Solution of Maxwell’s Equations for Six-Component Fields,” Electronics and Communication, (AEÜ), Vol. 31, pp. 116, 1977.

[45] D. Poljak, *Advanced Modeling in Computational Electromagnetic Compatibility*, John Wiley & Sons, Inc., New Jersey, 2007.

[46] H. H. Pennes, “Analysis of tissue and arterial blood temperature in resting forearm,” *J. Appl. Physiol.*, vol. 1, pp. 93–122, 1948.

[47] A. Hirata, O. Fujiwara, and T. Shiozawa, “Correlation between peak spatial-average SAR and temperature increase due to antennas attached to human trunk,” *IEEE Trans. Biomed. Eng.*, vol. 53, no. 8, pp. 1658–1664, Aug. 2006.

[48] A. Hirata, and O. Fujiwara, “The correlation between mass-averaged SAR and temperature elevation in the human head model exposed to RF near-fields from 1 to 6 GHz,” *Phys. Med. Biol.*, vol. 54, no. 23, pp. 7227–7238, 2009.

[49] R. Morimoto, I. Laakso, V. De Santis, and A. Hirata, “Relationship between peak spatial-averaged specific absorption rate and peak temperature elevation in human head in frequency range of 1-30 GHz,” *Phys. Med. Biol.*, vol. 61, no. 14, pp. 5406–5425, Jul. 2016.

[50] R. Morimoto, A. Hirata, I. Laakso, M. C. Ziskin, and K. R. Foster, “Time constants for temperature elevation in human models exposed to dipole antennas and beams in the frequency range from 1 to 30 GHz,” *Phys. Med. Biol.*, vol. 62, no. 5, pp. 1676–1699, Feb. 2017.

[51] A. Hirata, S. Kodera, K. Sasaki, J. Gomez-Tames, I. Laakso, A. Wood, S. Watanabe, and K. R. Foster, “Human exposure to radiofrequency energy above 6 GHz: review of computational dosimetry studies,” *Phys. Med. Biol.*, vol. 66, no. 8, pp. 08TR01, Apr. 2021.