Assessment of incident power density in different shapes of averaging area for radio-frequency exposure above 6 GHz

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Abstract

Objective. The International Commission on Non-Ionizing Radiation Protection guidelines and IEEE C95.1-2019 standard for human protection from local electromagnetic field exposure above 6 GHz state that absorbed (or epithelial) power density (APD) and incident power density (IPD), averaged over a square area, are internal and external physical quantities, respectively, that set the exposure limit. Per exposure standards, the measurement procedure and evaluation of the IPD have been established in technical standards, where a circular averaging area is recommended only for non-planar surfaces in IEC/IEEE 63195-1 and -2. In this study, the effects of two averaging shapes on the APD and IPD are evaluated computationally to provide new insights from the viewpoint of exposure standards. Approach. The relation between the APD, IPD, and the steady-state temperature rise (heating factor) in rectangular and human models for exposure to a single dipole, dipole arrays, and the Gaussian beams is investigated computationally with finite-difference method. Main results. The maximum differences in the heating factor of the APD and IPD for square and circular averaging areas were 4.1% and 4.4% for the antenna–model distance > 5 mm, respectively. These differences appear when the beam pattern on the model surface has an elliptical shape. For an antenna–model distance ≤ 5 mm and at frequencies ≤ 15 GHz, the heating factors for square averaging areas were not always conservative to those for circular ones (−7.8% for IPD), where only the antenna feed point are visible before beam formation. Significance. The heating factors of the APD and IPD for a circular averaging area are conservative for near-field exposure of canonical sources for frequencies up to 300 GHz, except for a beam with a significant major-to-minor axis ratio and an angle of 30°–60° to a square averaging area. This tendency would help bridge the gap between exposure and product standards.

1. Introduction

The new advanced technology for fifth-generation (5G) communication systems operates at high-frequency ranges, such as 24–28 GHz. The development of technologies and devices operating at frequencies above 6 GHz necessitates the revision of radio-frequency exposure guidelines for human protection and compliance assessment procedures. The exposure limits for human protection are established by the international commission on non-ionizing radiation protection (ICNIRP) (ICNRP 2020) and IEEE International Committee on Electromagnetic Safety (ICES) technical committee (TC) 95 (Bailey et al 2019, IEEE C95.1 2019). For frequencies above 6 GHz, the absorbed (or epithelial) power density (APD) is used as a metric, which is a surrogate of the steady-state temperature rise on the body surface (IEEE C95.1 2019, ICNRP 2020). In these two international guidelines and standards (IEEE C95.1 2019, ICNIRP 2020), an averaging area of the APD is 4 cm² in a square shape for a frequency range of 6–300 GHz. At frequencies higher than 30 GHz, an averaging area of 1 cm² should also be considered for small beam exposure. The limit of the incident power density (IPD) or (exposure) reference level corresponding to the APD is also defined in the international guidelines and standards for practical assessment purposes.

International standards for product assessment are established by international electrotechnical commission (IEC) TC 106 and IEEE ICES TC 34 to provide a procedure that adheres to the international...
exposure guidelines and standards. The measurement and computational assessment of the two power densities are established under IEC/IEEE JWG11 and 12, respectively (IEC TR 63170 ED1 2018, IEC/IEEE 63195-1 2021, IEC/IEEE 63195-2 2022). According to product standards for the assessment of the IPD (IEC TR 63170 ED1 2018, IEC/IEEE 63195-1 2021, IEC/IEEE 63195-2 2022), an averaging scheme of a circular shape is recommended only for non-planar surfaces for measuring the IPD because of the uncertainty in measurement compared to that of a square one. Note that the limit of the IPD is obtained from the APD (IEEE C95.1 2019, ICNIRP 2020), whose limit is derived from a temperature rise.

For this inconsistency, it is necessary to discuss the exposure standard or human protection rather than the product standard because the latter provides the assessment method for the metric and limit prescribed in the exposure standard. However, no attention has been paid to the relation between temperature rise and APD averaged over different averaging shapes with square and circular shapes.

Studies on human protection against exposure at frequencies above 6 GHz including 5G systems have been conducted regarding the APD or IPD over an averaging area with a square shape. The relationship between APD and the temperature rise in the human body is essential to setting the exposure limit. In addition, the effects of the curvature of the body surface for an area-averaged APD using various calculation schemes have been assessed in a recent study (Diao et al. 2020). Their results showed the heating factor for non-planar surfaces with a model curvature radius $>30$ mm at frequencies above 20 GHz agrees well with those for planar models. In addition, studies on exposure to frequencies above 6 GHz have evaluated appropriate exposure limits, physical quantities, and averaging areas through electromagnetic (EM) and thermal computations (Alekscev et al. 2005, 2008, Zhadobov et al. 2011, Morimoto et al. 2016, Foster et al. 2017, Hashimoto et al. 2017, 2017, Sasaki et al. 2017, Laakso et al. 2017a, Colombi et al. 2018, Funahashi et al. 2018, Ziskin et al. 2018, Gajda et al. 2019, Hirata et al. 2019, Christ et al. 2020, Hirata et al. 2021, Miura et al. 2021), as well as analytical approaches (Poljak and Cvetković 2020, Kapetanovic and Poljak 2021, Poljak et al. 2021). Furthermore, the intercomparison among several organizations, the differences in various definitions of the APD and IPD (Li et al. 2021a, 2021b), and the effect of the IPD on the oblique incidence of EM wave (Samaras and Kuster 2019, Nakae et al. 2020, Diao et al. 2021, Li and Sasaki 2022) have been studied.

Besides, studies on computational assessment (He et al. 2017, He et al. 2020, Diao and Hirata 2021, Xu et al. 2021, 2022) and measurement assessment of the power densities (Sasaki et al. 2019, Pfeifer et al. 2019b, 2019a, Teniou et al. 2020) have been conducted.

The ICNIRP guidelines (ICNIRP 2020) state that ‘ICNIRP uses a square averaging area of 4 cm$^2$ for $>6$–300 GHz as a practical protection specification. Moreover, from $>30$ to 300 GHz (where focal beam exposure can occur), an additional spatial average of 1 cm$^2$ is used to ensure that the operational adverse health effect thresholds are not exceeded over smaller regions.’ Similar epidermal power density specifications are described in IEEE C95.1 (IEEE C95.1 2019). This averaging area of 4 cm$^2$ approximately matches the face (side length of 2.2 cm) of a 10 g specific absorption rate (SAR) cubical volume, a metric for frequencies below 6 GHz. In contrast, in the ICNIRP laser guidelines (>300 GHz) (ICNIRP 2013), a circular shape of probe aperture is considered for measuring the power density. However, the rationale for a circular probe shape was not well discussed in the ICNIRP laser guideline. Therefore, a study on the discontinuation of the use of an averaging shape (<300 GHz) and probe shapes (>300 GHz) in both ICNIRP guidelines is of interest.

This study used a planar surface and the human anatomical model to compute the difference in averaged IPD and APD between square and circular averaging shapes in terms of the surface temperature rise. A single dipole and different antenna arrays were considered as the sources. Heating factors, defined as the ratio of the surface temperature rise in the steady-state to the APD and IPD, were assessed for square and circular averaging shapes. In addition, the corresponding differences obtained in the computational analysis were verified by those in the theoretical analysis, which may cover exposures with different beam patterns.

2. Model and methods

2.1. Rectangular and human body models

First, a three-dimensional (3D) skin homogeneous rectangle with a planar surface was used as the human surface model to evaluate the APD, IPD, and temperature rise. The dimension size of the model is $70 \times 200 \times 200$ mm at a frequency range of 6–30 GHz, whereas the dimension size of the model is $60 \times 120 \times 120$ mm for frequencies above 30 GHz, as shown in figure 1(a). The model resolution was 0.25 mm from 6 to 30 GHz and 0.1 mm above 30 GHz, considering numerical stability. Our previous study (Diao et al. 2021) investigated the effects of different skin layers in a rectangular model at a frequency of 30 GHz. The maximum relative standard deviation of the heating factor was within 3% for different skin models. Therefore, only the one-layer skin model was considered in this study.
In addition, a human anatomical model, the Japanese adult male model (TARO), was used to consider the realistic surface geometry of humans, as shown in figure 1(b). This model comprises 52 different tissues and organs (Nagaoka et al. 2004). An in-house smoothing algorithm was applied to the anatomical model (TARO) used in this study to avoid staircase errors (Taguchi et al. 2018). Specifically, the original resolution of the TARO model is 2 mm. The model was polygonized to reduce the number of edges of voxels, followed by smoothing. Next, the smoothed polygon model was voxelized to develop the corresponding model. The anatomical model has a resolution of 0.22 mm from 6 to 30 GHz, whereas the resolution is 0.11 mm above 30 GHz.

In Gabriel et al. (1996), a parametric model was validated for frequencies up to 20 GHz. For frequencies higher than 20 GHz, the expansion of the Cole–Cole dispersion model was verified using the measurement and parametric model in Sasaki et al. (2014). The variation in the temperature rise in tissue thickness is more dominant than in dielectric properties (Sasaki et al. 2017). In addition, heating factors for multi-layered models with skin tissue are consistent with those for models consisting of the epidermis and dermis tissue instead of the skin at 30 GHz (Diao et al. 2021). Therefore, in this study, the tissue dielectric and conductivity parameters of dry skin were modeled using a four-layer Cole–Cole dispersion model based on Gabriel et al. (1996).

2.2. Electromagnetic computation

Due to ethical considerations, obtaining an experimental temperature rise in the human body is difficult. This study used only computational and analytical approaches. The finite-difference time-domain (FDTD) method was used for EM calculations in this study (Taflove and Hagness 2003). The convolutional perfectly matched layer was used in the FDTD calculations so that radiated EM waves could be truncated at the side of the analytical region (Roden and Gedney 2000). Our in-house code can be validated through international intercomparison (Li et al. 2021a).

2.3. Thermal computation

The thermal analysis for calculating the temperature rise in the model was performed by solving a bioheat transfer equation (Pennes 1998). The SAR energy calculated in the first step was used as the heat source in a bioheat equation. The bioheat equation, which considers the thermal energy balance, i.e. heat conduction, blood perfusion, and electromagnetically induced heating (SAR), is expressed by equation (1):

\[
C(r)\rho(r)\frac{\partial T(r, t)}{\partial t} = \nabla \cdot (K(r)\nabla T(r, t)) + \rho(r)SAR(r) + M(r, t) - B(r, t)(T(r, t) - T_B(r, t)),
\]

\[T_B\] represents the blood temperature, \[T\] represents the tissue temperature, \[C, K, M, \text{and } B\] represent the specific tissue heat, the thermal conductivity of the tissue, metabolic heat generation, and blood perfusion term, respectively, \[\rho\] represents the mass density of the tissue, and \[t\] represents the variable in the time domain.

The blood temperature is assumed to be constant at 37 °C because the power absorption in the body is substantially smaller than the metabolic heat production of a male adult (∼100 W), causing a marginal body core...
The temperature rise (Kodera et al 2018). The boundary condition for equation (2) is given by

\[ -K(r) \frac{\partial T(r, t)}{\partial n} = H \cdot (T_s(r, t) - T_e(r, t)), \]

where \( H \) represents the heat transfer coefficient between air and the skin; \( T_s \) and \( T_e \) represent the skin temperature on the skin surface and ambient temperature, which is a constant value in the computational analysis, respectively. \( n \) denotes the normal component of the model surface. In this study, the steady-state temperature rise is primarily used to determine the heating factor. The temperature rise in the steady state was obtained by solving the bioheat equation using the boundary condition of equation (2) specifically, the left-hand side of equation (1) was equated to zero, which means that the steady-state temperature rise is time-independent. As a result, each term on the right-hand side can be treated as independent of time \( t \). As shown in table 1, most of the thermal parameters used in this study come from Hirata et al (2003), which are from Duck (1990). The blood perfusion rate of the skin was referred to Hasgall et al (2018). The blood perfusion rate varies depending on the skin tissue’s depth: the steady-state temperature rises variations \( \pm 15\% \) at frequencies above 6 GHz (Laakso et al 2017b). The heat transfer coefficient between the skin and air was 8 W (m\(^{-2}\)·°C\(^{-1}\)), the typical parameters at an ambient temperature of 23 °C (Hirata et al 2007).

### Table 1. Thermal parameters of human tissues used in equation (1).

| Tissue          | \( K \) [W (m\(^{-1}\)·°C\(^{-1}\)] | \( B \) [W(m\(^{-1}\)·°C\(^{-1}\)] | \( \rho \) [kg m\(^{-3}\)] |
|-----------------|---------------------------------|---------------------------------|-----------------------------|
| Skin            | 0.42                            | 7367                            | 1125                        |
| Muscle          | 0.50                            | 2700                            | 1047                        |
| Fat             | 0.25                            | 1626                            | 916                         |
| Cortical bone   | 0.37                            | 3400                            | 1990                        |
| Cancellous bone | 0.41                            | 3300                            | 1920                        |
| Cartilage       | 0.47                            | 9000                            | 1097                        |
| Nerve           | 0.46                            | 40 000                          | 1038                        |
| Dura            | 0.50                            | 9100                            | 1125                        |
| Gray matter     | 0.57                            | 40 000                          | 1038                        |
| White matter    | 0.62                            | 40 000                          | 1038                        |
| Cerebellum      | 0.57                            | 40 000                          | 1038                        |
| CSF             | 0.58                            | 0                               | 1007                        |
| Hypothalamus    | 0.40                            | 40 000                          | 1038                        |
| Vitreous humor  | 0.58                            | 0                               | 1009                        |
| Lens            | 0.40                            | 0                               | 1053                        |
| Retina          | 0.58                            | 0                               | 1026                        |
| Blood           | 0.56                            | 0                               | 1058                        |
| Tongue          | 0.54                            | 2700                            | 1047                        |
| Thalamus        | 0.57                            | 40 000                          | 1038                        |
| Pituitaria      | 0.57                            | 40 000                          | 1038                        |
| Pineal          | 0.57                            | 40 000                          | 1038                        |
| Trachea         | 0.47                            | 3700                            | 1100                        |
| Glandula salivaria | 0.42                         | 2350                            | 1000                        |
| Brain (averaged)| 0.57                            | 40 000                          | 1038                        |

### 2.4. Post processing

In the ICNIRP guidelines (ICNIRP 2020), the spatially area-averaged APD is defined as

\[ S_{ab} = \iint_A dx dy \int_0^{z_{\text{max}}} \rho(x, y, z) \cdot \text{SAR}(x, y, z) dz, \]

where \( z = 0 \) denotes the position coordinates of the body surface, \( A \) represents the averaging area, and \( \rho(x, y, z) \) and \( \text{SAR}(x, y, z) \) denote the tissue mass density and local SAR at the location \((x, y, z)\), respectively. The APD averages over 4 and 1 cm\(^2\) with square and circular shapes, respectively. \( z_{\text{max}} \) denotes the maximum depth in the z-direction of the model. Note that the penetration depth is small and localized near the model surface: the energy penetration depth into tissues with the dielectric properties of dry skin from Hasgall et al (2018), which were calculated from a one-dimensional model, are 1.9 and 0.18 mm at 10 GHz and 100 GHz, respectively (Foster et al 2018). The numerical models with the thickness sufficiently larger than the penetration depth of the electromagnetic wave were used in the computational analysis, as shown in figure 1(a). Therefore, the computational results at a relative depth location do not contribute to the APD results. We compensated for APD averaged over a circular shape in the computational analysis. Thus, the interpolation can be equal to 1 and
4 cm² to avoid a discrepancy between the averaging and integrated areas over the fraction of the circle voxel surface.

The heating factor is typically used as an exposure metric to measure the exposure level in the international guidelines and standards. Two heating factors are considered in this study. Specifically, the heating factor is the ratio of the steady-state temperature rise to the exposure metrics, respectively.

According to the technical standards (IEC/IEEE 63195-1 2021, IEC/IEEE 63195-2 2022), two IPD definitions can be considered, which are expressed as

\[
S_{\text{total}} = \frac{1}{2A} \iint_A |\text{Re}(E \times H^*)| \, dA, \tag{4}
\]

\[
S_n = \frac{1}{2A} \iint_A \text{Re}(E \times H^*) \cdot dA, \tag{5}
\]

where \(S_{\text{total}}\) represents the real part of the norm of the complex Poynting vector, and \(S_n\) represents the real part of the normal component to the model surface for the complex Poynting vector in the free space. \(A\) represents an averaging area. Please note that the IPD is determined in the free space without the presence of the model (IEEE C95.1 2019, ICNIRP 2020). In addition, the third definition of the IPD is specified only for proximity in ICNIRP guideline (ICNIRP 2020) and the technical standard (IEC/IEEE 63195-2 2022). The equation of the third IPD definition is expressed as follows.

\[
S_{\text{reactive}} = \frac{1}{2A} \iint_A [\text{Re}(E \times H^*)] + |\text{Im}(E \times H^*)| \, dA. \tag{6}
\]

In such a scenario, the imaginary part of the complex Poynting vector is dominant in the reactive field in equation (6).

However, ICNIRP (2020) states the IPD is no longer valid in the reactive region of a transmitting antenna. Thus, the third IPD definition was not considered in this study.

Furthermore, in this study, the percent difference in the heating factor for a square and circular averaging area is defined as

\[
\text{Diff} [\%] = \frac{H F_{\text{square}} - H F_{\text{circle}}}{H F_{\text{square}}} \cdot 100, \tag{7}
\]

\[
= \frac{1}{S_{\text{square}}} \cdot \frac{1}{S_{\text{circle}}} \cdot 100,
\]

where \(H F_{\text{square}}\) and \(H F_{\text{circle}}\) denote the heating factors for square and circular averaging areas, respectively. \(S_{\text{square}}\) and \(S_{\text{circle}}\) denote the power density for each averaging area of a square and circular shape, respectively.

Figure 2 shows the relationship between the averaging area and the anatomical head model. Square and circular averaging shapes are projected onto the non-planar surface in the human model, and the APD is derived using equation (3) by integrating into the depth direction (z-axis).

2.5. Exposure scenarios

In the 3D analysis, a single dipole antenna and dipole arrays are considered sources. For the dipole array configurations, 4 × 1 and 2 × 2 dipole arrays are considered to verify a tendency described in the analytical approach: the maximum difference in the heating factor of the APD for an averaging area with square and circular shapes is visible for an elliptical beam pattern with areas close to 4 and 1 cm². Figure 1 shows these antenna models. The length of each element for the dipole antenna and array was modeled at the half-wavelength to be the resonant frequency. As mentioned in section II-D, the heating factor, defined as the temperature rise relative to the power density, is used for human protection. In a frequency range, the impedance mismatch in the presence of the head is marginal, especially at distance >5 mm. Minor frequency adjustment for impedance matching was made at distance of 2 mm. These antennas are located at the side of the head model. The separation distances between the antenna and the models are 2, 5, 15, 30, and 50 mm. Voltage is applied to the input port in the antenna using the delta gap feed. The frequency range of 6–100 GHz was considered here. In addition, ideal Gaussian beams are considered; their beam diameter is set to 5, 10, 20, 40, and 100 mm, which can be applied to the APD on a planar model, not but to the IPD. Furthermore, the effect of different angles of incidence for the 4 × 1 dipole array is evaluated for TE- and TM-like polarizations. The dipole array was aligned along the y-axis for a TE-like polarized wave, as shown in figure 1(a). The incidence angles of 0°, 15°, 30°, 45°, and 60° were considered for the 4 × 1 dipole array. For TM-like polarized waves, the antenna element of the 4 × 1 dipole array was rotated 90° along the z-axis. The phase at each feed point is expressed as follows:
\[ \varphi_i = -(i-1)kd \cos \Phi, \]  

where \( \varphi_i \), \( i \), \( k \), \( d \), and \( \Phi \) denote the initial phase, the number of antenna elements, the wave number, separation, and the beam direction, respectively.

3. Computational results

3.1. Absorbed power density distribution in rectangular model

Figure 3 depicts the APD distribution for exposure from the single dipole, \( 4 \times 1 \) dipole, and \( 2 \times 2 \) dipole array antennas at the frequencies of 15, 40, and 80 GHz. The distributions at the separation distances of 2, 5, 15, 30, and 50 mm are shown in the figure. From figure 3(a), the APD for the single dipole antenna is widely distributed over the model surface at each antenna–model distance compared with those for the antenna arrays. The exposed area for the single dipole antenna was approximately 20 mm \( \times \) 20 mm for the distance of 15 mm at 80 GHz. The exposed area is the region where the EM energy has decayed to below \( 1/e \) of the maximum value. In contrast, figures 3(b) and (c) show that the power density is more localized at higher frequencies for the dipole antenna arrays than for the dipole antenna. The exposed area for the \( 4 \times 1 \) dipole array has an elliptically shaped field (beam) pattern at frequencies \( \geq 40 \) GHz for distances \( h \geq 15 \) mm. Conversely, a uniform pattern was observed for the \( 2 \times 2 \) dipole antenna array. For distances \( h \leq 5 \) mm, the distribution of the antenna feed for antenna arrays is visible at 15 GHz. At higher frequencies, a beam with a small diameter formed.

3.2. Theoretical analysis of APD for Gaussian beam exposure

The theoretical analysis covers more general beam patterns with a relatively large aspect ratio (e.g. a vertical length of 5 mm and a horizontal length of 95 mm), which are not considered in figure 3. In this section, the percent difference for square and circular averaging areas was evaluated using the Gaussian distribution of an elliptical shape, as shown in figure 4. The horizontal and vertical lengths of the elliptical beam pattern are 5–95 mm, respectively. The equation of the elliptical Gaussian beam is expressed by

\[
S_{\text{Gaussian}} = S_0 \exp \left\{ - \left( \frac{\cos^2 \theta}{\sigma_y^2} + \frac{\sin^2 \theta}{\sigma_z^2} \right) (y - y_0)^2 + \left( \frac{\sin^2 \theta}{\sigma_y^2} + \frac{\cos^2 \theta}{\sigma_z^2} \right) (z - z_0)^2 + 2 \cos \theta \sin \theta \left( - \frac{1}{\sigma_y^2} + \frac{1}{\sigma_z^2} \right) (y - y_0)(z - z_0) \right\},
\]

where \( \sigma_y, \sigma_z \) represent the horizontal and vertical lengths of the ellipse, \( y_0, z_0 \) represent the center coordinates of the ellipse, \( \theta \) denotes the rotation angle of the ellipse, and \( S_0 \) represents the amplitude of the power density. Tables 2 and 3 depict the percent difference in the heating factor of the APD obtained from equation (9) between square and circular averaging areas with an angle of 0°. From table 2, the difference in the heating factor

\[
\varphi_i = -(i-1)kd \cos \Phi,
\]
of the APD for an averaging area of 1 cm² is marginal, except for the case in which the horizontal or vertical length is 5 mm (see figure 3). In contrast, as shown in table 3, the percent difference for 4 cm² increases with an increase in the ratio of the horizontal to vertical length; 9.9% is the maximum difference when the horizontal and vertical lengths are 95 mm and 5 mm, respectively. The percent difference for 4 cm² was also 2.4%–6.3% for elliptical areas with a vertical length of 5 mm and horizontal lengths ranging from 15 to 25 mm. The percent

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**Figure 3.** APD distribution in the skin rectangular model for exposure to (a) single dipole, (b) 4 × 1 dipole antenna array, and (c) 2 × 2 dipole antenna array at frequencies of 15, 40, and 80 GHz. The distribution at the separation distances of 2, 5, 15, 30, and 50 mm are indicated in this figure. The power density is normalized with a maximum APD of 1 W m⁻².
difference was small for the uniform area in which the vertical length is almost equal to the horizontal length, as shown in tables 2 and 3. Furthermore, the effect of the rotation angle of the antenna arrays is studied using equation (9). Figure 5 shows the percent difference in the power density for various angles of ellipse patterns. The degree of the rotation is 0°, 15°, 30°, 45°, 60°, 75°, and 90°, respectively. From figure 5(a), the percent difference with angles of 30°–60° has a negative value, which implies that the heating factor for a circular averaging area is higher than that for a square one. This is because the considered exposure area for a square averaging area is larger than that for a circular area for an oblique exposed area around 30°–60°. This tendency appeared for the relatively large ratio of beam area longitudinal length $\geq 20$ mm and transverse length of 5 mm. A similar tendency can be observed for the averaging area of 1 cm². The maximum negative values were $-6.1\%$ and $-13.6\%$ for averaging areas of 1 and 4 cm² at an angle of 45°, as shown in figures 5(a) and (b).

3.3. Percent difference in APD for Gaussian beam exposures in skin model

Figures 6(a) and (b) indicate the percent difference in the heating factor of the APD for an ideal Gaussian beam for averaging areas of 1 and 4 cm². The beam diameters of 5, 10, 20, 40, and 100 mm were considered. Note that the difference is not existent for different averaging schemes in an ideal beam with a diameter smaller than the averaging area (1 cm²). Figure 6(a) shows the maximum difference in square and circular averaging areas for 1 cm² was 1.7% for a beam with a diameter of 10 mm, almost corresponding to a side length of 10 mm for an averaging area of 1 cm². The positive value of the percent difference indicates a case where the heating factor for a circular averaging area is lower than that for a square. A similar tendency can be observed for an averaging area of 4 cm²: the maximum difference is 1.5% in figure 6(b).

As indicated in figures 6(c) and (d), the heating factor of the APD averaged over a circular shape is comparable to that averaged over a square shape.

Figure 7 indicates the percent difference in the heating factor of the APD for elliptical Gaussian beams. As shown in figure 7, the beam pattern with a large aspect ratio resulted in the maximum difference. The maximum differences were 6.6% and 9.9% for the beam with the horizontal length of 5 mm and the vertical length of 90 mm for averaging areas of 1 cm² and 4 cm², respectively.

Figure 8(a) depicts the percent difference in the heating factor of the APD for a single dipole antenna at the antenna–model distances of 2, 5, 15, 30, and 50 mm. As shown in figure 8(a), there is no clear difference in the heating factor for square and circular averaging areas at each antenna–model distance. The maximum differences in the heating factor for square and circular averaging areas were 1.4% and 1.3% for averaging areas of 1 and 4 cm².

The longitudinal length of the exposed beam area is approximately 21 mm for the distances of 15 and 8 mm for the distance of 5 mm, which corresponds to the size of the averaging area.

Figure 8(b) shows the difference in the heating factor of the APD for square and circular averaging areas for the $4 \times 1$ dipole array. As shown in figure 8(b), for the distance $\leq 5$ mm, a significant difference in the heating factor can be observed. From figures 8(b) and (c), for the distance $\geq 15$ mm, the percent differences in the heating factor for the $4 \times 1$ dipole arrays are higher than those for the single and $2 \times 2$ dipole arrays. The maximum difference was 4.1% and 1.7% for the $4 \times 1$ and $2 \times 2$ dipole array antennas, except for the distance close to the model $\leq 5$ mm, respectively. In contrast, from figures 8(a) and (c), the differences in the heating factor for the $2 \times 2$ dipole array are comparable to those for the single dipole, except for those for the distance of 2 mm at 15 GHz.
Table 2. Percent difference in APD for square and circular averaging areas of 1 cm² in the elliptical beam pattern based on equation (9) with a rotation angle of 0°. The horizontal and vertical lengths in the elliptical area from 5 to 95 mm are considered.

| Vertical length [mm] | 5    | 10   | 15   | 20   | 25   | 30   | 35   | 40   | 45   | 50   | 55   | 60   | 65   | 70   | 75   | 80   | 85   | 90   | 95   |
|----------------------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| 5                    | 0.28 | 3.00 | 4.70 | 5.50 | 5.90 | 6.20 | 6.30 | 6.40 | 6.50 | 6.60 | 6.60 | 6.60 | 6.60 | 6.60 | 6.60 | 6.70 | 6.70 | 6.70 | 6.70 |
| 10                   | 3.00 | 1.40 | 1.50 | 1.60 | 1.70 | 1.70 | 1.80 | 1.80 | 1.80 | 1.80 | 1.80 | 1.80 | 1.80 | 1.80 | 1.90 | 1.90 | 1.90 | 1.90 | 1.90 |
| 15                   | 4.70 | 1.50 | 0.95 | 0.83 | 0.80 | 0.78 | 0.78 | 0.77 | 0.77 | 0.77 | 0.77 | 0.77 | 0.77 | 0.77 | 0.76 | 0.76 | 0.76 | 0.76 | 0.76 |
| 20                   | 5.50 | 1.60 | 0.83 | 0.62 | 0.53 | 0.49 | 0.47 | 0.45 | 0.44 | 0.44 | 0.43 | 0.42 | 0.42 | 0.42 | 0.42 | 0.42 | 0.42 | 0.42 | 0.42 |
| 25                   | 5.90 | 1.70 | 0.80 | 0.53 | 0.42 | 0.37 | 0.34 | 0.32 | 0.30 | 0.29 | 0.29 | 0.28 | 0.28 | 0.27 | 0.27 | 0.27 | 0.27 | 0.27 | 0.27 |
| 30                   | 6.20 | 1.70 | 0.78 | 0.49 | 0.37 | 0.31 | 0.27 | 0.25 | 0.23 | 0.22 | 0.21 | 0.20 | 0.20 | 0.20 | 0.19 | 0.19 | 0.19 | 0.19 | 0.19 |
| 35                   | 6.30 | 1.80 | 0.78 | 0.47 | 0.34 | 0.27 | 0.23 | 0.20 | 0.19 | 0.18 | 0.17 | 0.16 | 0.16 | 0.15 | 0.15 | 0.15 | 0.14 | 0.14 | 0.14 |
| 40                   | 6.40 | 1.80 | 0.77 | 0.45 | 0.32 | 0.25 | 0.20 | 0.18 | 0.16 | 0.15 | 0.14 | 0.13 | 0.13 | 0.12 | 0.12 | 0.12 | 0.11 | 0.11 | 0.11 |
| 45                   | 6.50 | 1.80 | 0.77 | 0.44 | 0.30 | 0.23 | 0.19 | 0.16 | 0.14 | 0.13 | 0.12 | 0.11 | 0.10 | 0.10 | 0.09 | 0.09 | 0.09 | 0.09 | 0.09 |
| 50                   | 6.50 | 1.80 | 0.77 | 0.44 | 0.29 | 0.22 | 0.18 | 0.15 | 0.13 | 0.12 | 0.11 | 0.10 | 0.09 | 0.09 | 0.09 | 0.08 | 0.08 | 0.08 | 0.08 |
| 55                   | 6.60 | 1.80 | 0.77 | 0.43 | 0.29 | 0.21 | 0.17 | 0.14 | 0.12 | 0.11 | 0.10 | 0.09 | 0.09 | 0.08 | 0.08 | 0.08 | 0.07 | 0.07 | 0.07 |
| 60                   | 6.60 | 1.80 | 0.77 | 0.43 | 0.28 | 0.20 | 0.16 | 0.13 | 0.11 | 0.10 | 0.09 | 0.08 | 0.08 | 0.07 | 0.07 | 0.07 | 0.06 | 0.06 | 0.06 |
| 65                   | 6.60 | 1.80 | 0.77 | 0.42 | 0.28 | 0.20 | 0.16 | 0.13 | 0.11 | 0.09 | 0.08 | 0.08 | 0.07 | 0.07 | 0.07 | 0.07 | 0.06 | 0.06 | 0.05 |
| 70                   | 6.60 | 1.90 | 0.77 | 0.42 | 0.27 | 0.20 | 0.15 | 0.12 | 0.10 | 0.09 | 0.08 | 0.07 | 0.07 | 0.07 | 0.06 | 0.06 | 0.05 | 0.05 | 0.05 |
| 75                   | 6.60 | 1.90 | 0.77 | 0.42 | 0.27 | 0.19 | 0.15 | 0.12 | 0.10 | 0.09 | 0.08 | 0.07 | 0.07 | 0.06 | 0.06 | 0.05 | 0.05 | 0.05 | 0.05 |
| 80                   | 6.60 | 1.90 | 0.76 | 0.42 | 0.27 | 0.19 | 0.15 | 0.12 | 0.10 | 0.08 | 0.07 | 0.06 | 0.06 | 0.05 | 0.05 | 0.05 | 0.04 | 0.04 | 0.04 |
| 85                   | 6.70 | 1.90 | 0.76 | 0.42 | 0.27 | 0.19 | 0.14 | 0.11 | 0.09 | 0.08 | 0.07 | 0.06 | 0.05 | 0.05 | 0.05 | 0.04 | 0.04 | 0.04 | 0.04 |
| 90                   | 6.70 | 1.90 | 0.76 | 0.42 | 0.27 | 0.19 | 0.14 | 0.11 | 0.09 | 0.08 | 0.07 | 0.06 | 0.05 | 0.05 | 0.05 | 0.04 | 0.04 | 0.04 | 0.04 |
| 95                   | 6.70 | 1.90 | 0.76 | 0.42 | 0.26 | 0.19 | 0.14 | 0.11 | 0.09 | 0.08 | 0.07 | 0.06 | 0.05 | 0.05 | 0.05 | 0.04 | 0.04 | 0.04 | 0.04 |
Table 3. Percent difference in APD for square and circular averaging areas of 4 cm$^2$ in the elliptical beam pattern based on equation (9) with a rotation angle of 0°.

| Vertical length [mm] | 5  | 10 | 15 | 20 | 25 | 30 | 35 | 40 | 45 | 50 | 55 | 60 | 65 | 70 | 75 | 80 | 85 | 90 | 95 |
|---------------------|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| 5                   | 0.01 | 0.31 | 2.40 | 6.30 | 7.40 | 8.00 | 8.50 | 8.90 | 9.10 | 9.30 | 9.40 | 9.50 | 9.60 | 9.70 | 9.80 | 9.80 | 9.90 | 9.90 |
| 10                  | 0.31 | 0.33 | 1.50 | 3.00 | 4.00 | 4.70 | 5.20 | 5.50 | 5.80 | 5.90 | 6.10 | 6.20 | 6.20 | 6.30 | 6.40 | 6.40 | 6.50 | 6.50 |
| 15                  | 2.40 | 1.50 | 1.30 | 1.70 | 2.10 | 2.40 | 2.70 | 2.80 | 2.90 | 3.00 | 3.10 | 3.20 | 3.20 | 3.30 | 3.30 | 3.30 | 3.30 | 3.30 |
| 20                  | 4.70 | 3.00 | 1.70 | 1.40 | 1.40 | 1.50 | 1.60 | 1.60 | 1.70 | 1.70 | 1.70 | 1.70 | 1.80 | 1.80 | 1.80 | 1.80 | 1.80 | 1.80 |
| 25                  | 6.30 | 4.00 | 2.10 | 1.40 | 1.20 | 1.10 | 1.10 | 1.10 | 1.10 | 1.10 | 1.10 | 1.10 | 1.10 | 1.10 | 1.10 | 1.10 | 1.10 | 1.10 |
| 30                  | 7.40 | 4.70 | 2.40 | 1.50 | 1.10 | 0.96 | 0.88 | 0.84 | 0.82 | 0.81 | 0.80 | 0.79 | 0.79 | 0.78 | 0.78 | 0.78 | 0.77 | 0.77 |
| 35                  | 8.00 | 5.20 | 2.70 | 1.60 | 1.10 | 0.88 | 0.77 | 0.71 | 0.67 | 0.64 | 0.62 | 0.61 | 0.60 | 0.59 | 0.58 | 0.58 | 0.57 | 0.57 |
| 40                  | 8.50 | 5.50 | 2.80 | 1.60 | 1.10 | 0.84 | 0.71 | 0.63 | 0.57 | 0.54 | 0.51 | 0.50 | 0.48 | 0.47 | 0.46 | 0.46 | 0.45 | 0.44 |
| 45                  | 8.90 | 5.80 | 2.90 | 1.70 | 1.10 | 0.82 | 0.67 | 0.57 | 0.51 | 0.47 | 0.44 | 0.42 | 0.41 | 0.39 | 0.38 | 0.38 | 0.37 | 0.36 |
| 50                  | 9.10 | 5.90 | 3.00 | 1.70 | 1.10 | 0.81 | 0.64 | 0.54 | 0.47 | 0.43 | 0.40 | 0.37 | 0.35 | 0.34 | 0.33 | 0.33 | 0.32 | 0.31 |
| 55                  | 9.30 | 6.10 | 3.10 | 1.70 | 1.10 | 0.80 | 0.62 | 0.51 | 0.44 | 0.40 | 0.36 | 0.34 | 0.32 | 0.30 | 0.29 | 0.28 | 0.27 | 0.26 |
| 60                  | 9.40 | 6.20 | 3.20 | 1.70 | 1.10 | 0.79 | 0.61 | 0.50 | 0.42 | 0.37 | 0.34 | 0.31 | 0.29 | 0.27 | 0.26 | 0.25 | 0.24 | 0.23 |
| 65                  | 9.50 | 6.20 | 3.20 | 1.80 | 1.10 | 0.79 | 0.60 | 0.48 | 0.41 | 0.35 | 0.32 | 0.29 | 0.27 | 0.25 | 0.24 | 0.22 | 0.21 | 0.20 |
| 70                  | 9.60 | 6.30 | 3.20 | 1.80 | 1.10 | 0.78 | 0.59 | 0.47 | 0.39 | 0.34 | 0.30 | 0.27 | 0.25 | 0.23 | 0.22 | 0.21 | 0.20 | 0.19 |
| 75                  | 9.70 | 6.40 | 3.30 | 1.80 | 1.10 | 0.78 | 0.58 | 0.46 | 0.38 | 0.33 | 0.29 | 0.26 | 0.24 | 0.22 | 0.20 | 0.19 | 0.18 | 0.17 |
| 80                  | 9.80 | 6.40 | 3.30 | 1.80 | 1.10 | 0.78 | 0.58 | 0.46 | 0.38 | 0.32 | 0.28 | 0.25 | 0.22 | 0.21 | 0.19 | 0.18 | 0.17 | 0.16 |
| 85                  | 9.80 | 6.40 | 3.30 | 1.80 | 1.10 | 0.78 | 0.58 | 0.45 | 0.37 | 0.31 | 0.27 | 0.24 | 0.22 | 0.20 | 0.18 | 0.17 | 0.16 | 0.15 |
| 90                  | 9.90 | 6.50 | 3.30 | 1.80 | 1.10 | 0.77 | 0.57 | 0.45 | 0.36 | 0.31 | 0.26 | 0.23 | 0.21 | 0.19 | 0.17 | 0.16 | 0.15 | 0.14 |
| 95                  | 9.90 | 6.50 | 3.30 | 1.80 | 1.10 | 0.77 | 0.57 | 0.44 | 0.36 | 0.30 | 0.26 | 0.23 | 0.20 | 0.18 | 0.17 | 0.16 | 0.14 | 0.13 |
3.4. Percent difference of APD in anatomical model for dipole antenna and arrays

Figure 9 shows the frequency-dependent percent difference in the heating factor of the APD for the single and $4 \times 1$ dipole arrays using an anatomical human head model for the distance of 5 and 15 mm. The IPD is determined in free space without the presence of the model. Therefore, the percent difference in the heating factor of the averaged IPD is independent of the model based on equation (7). The percent difference in the heating factor of the IPD in the anatomical model is not shown in this figure. For an average area of 4 cm$^2$, the percent differences in the heating factor for the single and $4 \times 1$ dipole arrays are mainly positive values.
comparable with those in the rectangular model (see figure 8). In contrast, for 1 cm², a significant percent difference of 0.3%–3.9% in the heating factor is observed for a single dipole compared with those in the rectangular model.

3.5. Percent difference of IPD for dipole antenna and array
Figure 10 depicts the heating factor of the IPD obtained from equations (4) and (5) for the single, 4 × 1 dipole, and 2 × 2 dipole arrays in a rectangular skin model. Figures 10(a) and (c) show that the maximum differences in the heat factor of the IPD for the single and four-element dipole arrays are comparable with those for the APD. However, for a distance ≤5 mm, a significant difference in the negative value can be observed at 15 GHz. In addition, the difference in the definition of the IPD between the normal component and the norms of the power density for different averaging schemes was marginal.

3.6. Percent difference in APD from dipole array at different angles of incidence
Figure 11 depicts the APD distribution for different angles of incidence for the 4 × 1 dipole array for TE-like and TM-like polarized waves. The antenna–model distance was 30 mm. As shown in figure 11, the shape of the exposed beam area is almost identical to the incidence angles of 0°–60° for TE- and TM-like polarized waves. Note that the distance of 30 mm was considered to realize a significant angle of incidence.

Figure 12 depicts the percent difference in the heating factor of the APD for different angles of incidence for the 4 × 1 dipole array for TE- and TM-like polarized waves. For averaging areas of 1 and 4 cm², the percent differences are below 3% for both TE- and TM-like polarized waves, as shown in figure 12. In addition, the percent difference decreases as the incidence angle increases.

4. Discussion and summary
In this study, the difference in the heating factor of the APD and IPD averaged over the square, and circular shapes are studied in the rectangular skin model and human anatomical model. The APD is an important metric for setting exposure limits in the international guidelines and standards for protection from excessive skin temperature rise. The IPD is derived from the APD as the reference level or permissible power density considering the reflection and transmittance coefficient at the body surface for practical evaluations. The heating factor is defined as the ratio of the steady-state temperature rise to the IPD or APD. Therefore, the steady-state temperature rise was only computed in this study. Furthermore, the APD for averaging areas in the anatomical model defined in figure 2 was only computed from the viewpoint of the exposure standards rather than the product safety. Moreover, the rotation of the exposed area was considered to find a worst-case exposure in the theoretical analysis rather than to consider the effect of the rotation of an averaging area specified in the product safety.

The beam pattern of the exposed area for the practical exposure scenario differs depending on the antenna–model distance and the antenna type. The beam patterns for the single dipole, and the 2 × 2 dipole arrays are rather circular, whereas the exposed area is elliptical for 4 × 1 dipole arrays (see figure 3).
Theoretical analysis was used to explore beam patterns with a large aspect ratio (see figure 4). The maximum percent difference of 4.1% for the $4 \times 1$ dipole array in the EM computation was close to the analytical results of 2.4%–6.3% for elliptical areas with a vertical length of 5 mm and horizontal lengths ranging from 15 to 25 mm (see table 3 and figure 8). The results indicated that a beam pattern with a large aspect ratio resulted in the maximum difference in the power density for square and circular averaging areas. The maximum difference was 9.9%, with a rotation angle of $0^\circ$ (see table 3). The exposed area, which led to the corresponding percent difference, was not obtained in the EM computation in this study. Therefore, the theoretical analysis achieved a larger percent difference. In addition, the heating factor of the IPD in an elliptical Gaussian beam for a circular averaging shape is lower than that for a square shape, except for an angle of the beam pattern of $30^\circ$–$60^\circ$. For an angle of $45^\circ$, the heating factor for a circular averaging area is higher than that for a square one by approximately 6% and 13% for 1 and 4 cm$^2$ (see figure 5).

The ideal Gaussian beam showed that the maximum difference in the heating factor could be observed when the beam diameter corresponds to averaging areas of 4 and 1 cm$^2$ (see figure 6). The corresponding results for circular beam were consistent with the theoretical analysis results (see tables 2, 3 and figure 6). Additionally, the percent difference in elliptic beam is almost identical to the analytical solution (see tables 2 and 3, and figure 7). A minimum diameter of 5 mm was defined, which can be observed at a distance $\geq 5$ mm, considering the effect.
caused by the field pattern, where only the antenna feed point can be seen before beam formation for antenna arrays at a distance of 2 mm. For an averaging area of 4 cm², the heating factor for beam diameters of 5 mm exceeds 0.025 °C·m² W⁻¹: the reference value for determining the IPD limit in the international guideline for protection against the temperature rise in the human body (see figure 6(d)). Wireless terminals such as a body-worn device might be considered for a scenario of beam exposure at a very small diameter. Although the heating factor for beam diameters of 5 mm exceeds 0.025 °C·m² W⁻¹, which is the reference value for determining the IPD limit in the international guideline (ICNIRP 2020), it may be considered a conservative exposure scenario because of the small output power of a body-worn wireless device in practice. A previous study (Li et al 2021a) on the intercomparison of the heating factor has reported similar results.

For relatively uniform beam patterns, such as ideal Gaussian beams and exposure to the single dipole and 2 × 2 dipole arrays, the tendency of the maximum differences was the same. The percent differences in the heating factor for square and circular averaging areas are less than 2% (see tables 2, 3, figures 6, and 8(a) and (c)). In contrast, the maximum percent difference in the heating factor for the 4 × 1 dipole array for the distance ≥15 mm was 4.1%, which is attributable to the elliptical beam pattern: horizontal length of 8.2 mm and vertical length of 21.2 mm at 80 GHz for the model–antenna distance of 15 mm (see figure 3(b)).

Hence, the numerical approach using the human anatomical model was considered to validate this study’s findings obtained using the rectangular skin model. The percent difference for the 4 × 1 dipole array in the human anatomical model was almost similar to the tendency in the rectangular skin model. In contrast, the value for the single dipole with an averaging area of 1 cm² was higher than that in the rectangular skin model (see figure 9). This is attributable to the complex surface in the anatomical model. The percent differences between antennas for averaging areas of 1 and 4 cm² were less than 4% (see figure 9).

The tendency of the percent difference in the IPD was almost identical to that in the APD (see figure 10). The IPD and APD differ only in EM energy due to the reflection and transmittance coefficients. Therefore, the percent differences for the IPD for square and circular averaging shapes were comparable to those for the APD.

Nearby, for very near-field exposure, with the distance ≤5 mm, the horizontal row of antenna feeding points caused the larger difference for averaging shapes for the 4 × 1 dipole array (see figures 3(b), 8(b), and 10(b)). The negative value of the percent difference (~7.8%) for the averaging area of 1 cm² for the distance of 2 mm at 15 GHz was due to the field pattern, where only the antenna feed point can be seen before beam formation in proximity (see figures 3(c) and 10(c)). Specifically, the distance between antenna elements of the 2 × 2 dipole array is approximately 10 mm, matching the half-wavelength at 15 GHz, approximately corresponding to the worst-case exposure. Therefore, a square averaging area of 1 cm² cover the area of four antenna feeds, but not for a circular averaging area. The effects of computational errors caused by factors, such as the resolution of antenna feed points and antenna types, are also mentioned: the maximum relative standard deviation is approximately
Figure 10. The percent difference in the heating factor of the IPD for (a) the single dipole, (b) $4 \times 1$ dipole array, and (c) $2 \times 2$ dipole array in the rectangular skin model. The two definitions of the IPD for averaging areas of 4 and 1 cm$^2$ are obtained from equations (4) and (5), respectively.
11% for dipole arrays (Li et al 2021a). Further studies on the corresponding exposure scenario at proximity to the source may be required for product safety.

Finally, the effects of square and circular averaging shapes for different incidence angles were marginal: the percent difference was 0.3%–2.4% for the incidence angle of 0°–60° (see figures 11 and 12). The percent
difference decreases with the increase of the incidence angle, because of uniform field distribution in the averaging area, i.e. an increase in the exposed area with an increasing incidence angle.

The limitation of this study is that all exposure scenarios cannot be covered in one study, even though typical exposure scenarios considered in the exposure standards are covered. One challenge for further discussion is the definition of the APD averaging scheme for curvature surfaces, and this is currently discussed by a working group of IEEE ICES TC 95. Further discussion may be required after the consensus on more complex geometry.

In conclusion, the difference in the heating factor of the APD and IPD for circular and square averaging areas was evaluated using the EM computation and analytical approaches. The maximum difference can be observed for the elliptical pattern, which is close in length to the averaging area. The heating factors of the APD and IPD averaged over a circular averaging shape were conservative to that of those averaged over a square averaging area for frequencies up to 300 GHz, except for the angle of the beam pattern of 30°–60°.

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References

Alekseev S I, Radzievsky A A, Logani M K and Ziskin M C 2008 Millimeter wave dosimetry of human skin Bioelectromagnetics 29 65–70
Alekseev S I, Radzievsky A A, Szabo I and Ziskin M C 2005 Local heating of human skin by millimeter waves: effect of blood flow Bioelectromagnetics 26 489–501
Bailey W H et al 2019 Synopsis of IEEE Std C95.1™–2019 ‘IEEE standard for safety levels with respect to human exposure to electric, magnetic, and electromagnetic fields, 0 Hz to 300 GHz’ IEEE Access 7 171346–56
Christ A, Samaras T, Neufeld E and Kuster N 2020 Limitations of incident power density as a proxy for induced electromagnetic fields Bioelectromagnetics 41 348–359
Colombi D, Thors B, Tornevik C and Balzano Q 2018 RF energy absorption by biological tissues in close proximity to millimeter-wave 5G wireless equipment IEEE Access 6 4974–81
Diao Y and Hirata A 2021 Exposure assessment of array antennas at 28 GHz using hybrid spherical near-field transformation and FDTD method IEEE Trans. Electromagn. Comput. 63 1690–8
Diao Y, Li K, Sasaki K, Kodera S, Laakso I, Hajj W E and Hirata A 2021 Effect of incidence angle on the spatial-average of incident power density definition to correlate skin temperature rise for millimeter wave exposures IEEE Trans. Electromagn. Comput. 63 1709–16
Diao Y, Rashed E A and Hirata A 2020 Assessment of absorbed power density and temperature rise for nonplanar body model under electromagnetic exposure above 6 GHz Phys. Med. Biol. 65 1–15
Duck F A 1990 Physical Properties of Tissues: A Comprehensive Reference Book (New York: Academic)
Foster K R, Ziskin M C and Balzano Q 2017 Thermal modeling for the next generation of radio-frequency exposure limits: commentary Health Phys. 113 41–53
Foster K R, Ziskin M C, Balzano Q and Hirata A 2018 Thermal analysis of averaging of times in radio-frequency exposure limits above 1 GHz IEEE Access 6 74536–46
Funahashi D, Hirata A, Kodera S and Foster K R 2018 Area-averaged transmitted power density at skin surface as metric to estimate surface temperature elevation IEEE Access 6 77656–74
Gabriel S, Lau R W and Gabriel G C 1996 The dielectric properties of biological tissues: III. Parametric models for the dielectric spectrum of tissues Phys. Med. Biol. 41 2271–93
Gajda G B, Lemay E and Paradis J I 2019 Model of steady-state temperature rise in multilayer tissues due to narrow-beam millimeter-wave radiofrequency field exposure Health Phys. 117 254–66
Hassgall P A, Gennaro F, di Baumgartner C, Neufeld E, Lloyd B, Gosselin M C, Payne D, Klingenbock A and Kuster N 2018 ITIS Database for thermal and electromagnetic parameters of biological tissues, Version 4.0 It’s Is (https://www.itis.ethz.ch/virtual-population/tissue-properties/overview)
Hashimoto Y, Hirata A, Morimoto R, Aonuma S, Laakso I, Jokela K and Foster K R 2017 On the averaging area for incident power density for human exposure limits at frequencies over 6 GHz Phys. Med. Biol. 62 3124–38
He W, Xu B, Gustafsson M, Ying Z and He S 2017 RF compliance study of temperature elevation in human head model around 28 GHz for 5G user equipment application: simulation analysis IEEE Access 6 8330–8
He W, Xu B, Yao Y, Colombi D, Ying Z and He S 2020 Implications of incident power density limits on power and EIRP levels of 5G millimeter-wave user equipment IEEE Access 8 148214–25
Hirata A, Funahashi D and Kodera S 2019 Setting exposure guidelines and product safety standards for radio-frequency exposure at frequencies above 6 GHz brief review Ann. des Telecommun./Ann. Telecommun. 74 17–24
Hirata A, Kodera S, Sasaki K, Gomez-Tames J, Laakso I, Wood A, Watanabe S and Foster K R 2021 Human exposure to radiofrequency energy above 6 GHz: review of computational dosimetry studies Phys. Med. Biol. 66 1–20
Hirata A, Morita M and Shiozawa T 2003 Temperature increase in the human head due to a dipole antenna at microwave frequencies IEEE Trans. Electromagn. Comput. 45 109–16
Hirata A, Watanabe S, Fujisawa O, Kojima M, Sasaki K and Shiozawa T 2007 Temperature elevation in the eye in an anatomically based human head models for plane-wave exposures Phys. Med. Biol. 52 6389–99
ICNIRP 2013 ICNIRP guidelines on limits of exposure to laser radiation of wavelengths between 180 nm and 1,000 μm Health Phys. 105 271–295
ICNIRP 2020 Guidelines for limiting exposure to electromagnetic fields (100 kHz to 300 GHz) Health Phys. 118 483–524
IEC TR 63170 ED1 2018 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
