Power Absorption and Skin Temperature Rise from Simultaneous Near-field Exposure at 2 and 28 GHz

Norika Miura\(^1\), Sachiko Kodera\(^1\), Member, IEEE, Yinliang Diao\(^1\), Member, IEEE, Junji Higashiyama\(^2\), Yasunori Suzuki\(^2\), and Akimasa Hirata\(^{1,3}\), Fellow, IEEE

\(^1\)Department of Electrical and Mechanical Engineering, Nagoya Institute of Technology, Nagoya 466-8555, Japan
\(^2\)Department of 6G Laboratories, NTT DOCOMO, INC., Kanagawa 239-8536, Japan
\(^3\)Center of Biomedical Physics and Information Technology, Nagoya Institute of Technology, Nagoya 466-8555, Japan

Corresponding author: Akimasa Hirata (e-mail: ahirata@nitech.ac.jp).

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ABSTRACT In international guidelines and standards for human protection from electromagnetic fields, mass-averaged specific absorption rate (SAR) is used as a metric to prevent excessive temperature rise at frequencies up to 6 GHz. Above this transition frequency, including the frequency region assigned to fifth-generation (5G) wireless communication systems, area-averaged absorbed power density (APD) or epithelial power density is used as a physical quantity to specify restrictions on human exposure. In 5G wireless systems, frequencies above and below 6 GHz may be used simultaneously. The effect of the superposition of SAR and APD on temperature rise should be considered, especially regarding the prevention of excessive surface temperature. Herein, we considered simultaneous exposure from inverted-F antenna and patch antenna array operating at 2 and 28 GHz, respectively. Computational results showed that the effect of superposition was marginal. This result is attributable to the heat diffusion length in biological tissues (~10 mm). The effect of the superposition was higher than 15% only when the patch antenna array and inverted-F antenna were separated by less than 50 mm for the 5 mm antenna-body separation.

INDEX TERMS Human protection, Dosimetry, Standardization

I. INTRODUCTION

For human protection from electromagnetic fields (<300 GHz), the international guidelines and standards were established by International Commission on Non-Ionizing Radiation Protection (ICNIRP) \([1], [2]\) and IEEE International Committee on Electromagnetic Safety (ICES) \([3], [4]\), which are mentioned in documents of the World Health Organization. A revised version of the IEEE ICES C95.1 standard (0–300 GHz) was issued in 2019 \([5]\). Moreover, a revised version of the ICNIRP guidelines (100 kHz–300 GHz) was issued in 2020 \([6]\).

According to the international guidelines and standards, the specific absorption rate (SAR) averaged over 10 g of tissue is used as a metric at frequencies below 6 GHz, and the absorbed power density (APD) or epithelial power density averaged over 4 cm\(^2\) is employed above 6 GHz for local exposure \([5], [6]\). The rationale for the peak spatial-average SAR over 10 g of tissue is being good surrogate for temperature rise \([7]–[9]\), for protection from excessive temperature rise both in the surface and internal tissues (e.g., brain \([10]–[14]\), eye lens \([15]–[18]\), and trunk \([19], [20]\)), whereas APD is designated for preventing excessive surface temperature rise \([21]–[23]\). Recently, the assessments of electromagnetic fields and temperature rise for exposures above 6 GHz have been conducted by different groups for realistic exposure scenarios \([24]–[30]\), commonly adopted radiation sources include antenna arrays formed by such as dipoles, patches, and slots. Methods for assessing free-space power density were proposed for the near field exposures \([31]–[34]\). The effect of incident angle on the incident power density and skin surface temperature for beamforming antenna arrays and plane incident waves have been studied in \([35], [36]\). Recent review for exposure to EMF above 6 GHz can be found in \([37]–[41]\).
According to the revised international standards and guidelines, the summation of SAR and APD normalized using the corresponding limits should be less than 1 for simultaneous exposure to electromagnetic fields below and above 6 GHz. However, no references have been cited in the corresponding part for such emerging exposures. It is unclear how much conservativeness is warranted in the formula considering new evaluation quantities. If the equation is overconservative, such simultaneous radiofrequency use may be inhibited. Considering the rationale of the guidelines and standard, the surface temperature should be dominant because, even for exposure only below 6 GHz the brain temperature rise should be less than 1°C [6].

The corresponding product safety standard is also under development by the joint group of IEEE ICES Technical Committee (TC) 34 and International Electrotechnical Commission (IEC) TC 106. In practice, simultaneous exposure from antennas implemented in a handset operating at different frequencies, especially above and below 6 GHz, should be assessed. For example, simultaneous exposure at the frequencies of fourth- and fifth-generation (4G and 5G) wireless communication systems may occur in data transmission while talking. Until now, the temperature rise caused by simultaneous exposure, both above and below 6 GHz components, has not been evaluated.

This study computes the temperature rise in the head surface for simultaneous local exposure at 2 and 28 GHz to evaluate if the evaluation equation in new guidelines and standard is effective. The primary purpose of this study is to provide scientific information for future standardization.

II. COMPUTATIONAL MODELS AND METHODS

A. MULTILAYER CUBIC AND ANATOMICAL HEAD MODELS

A three-dimensional (3D) seven-layer cubic head model [22], [42] for simulating a human head (Fig. 1a) was considered for our initial analysis. The dimensions of the cube were 7 cm × 20 cm × 25 cm, and the resolution was 0.25 mm.

To confirm the results obtained from the cube, we considered a partial head model captured from temporal regions, including the pinna region of a realistic human model (hereinafter referred to as the side head model). The original human model was a Japanese male model named TARO developed using magnetic resonance images [43]. This model comprised more than 50 tissues/organs, including the skin, muscle, and bone. The partial head model with a resolution of 0.22 mm comprised 17 tissues. The side head model was inclined to consider a realistic exposure scenario (Fig. 1b).

B. ELECTROMAGNETIC ANALYSIS

Finite-difference time-domain (FDTD) method [44] was employed for electromagnetic dosimetry in the human models exposed to radiofrequency fields emitted from a near-field source. These grid resolutions satisfy the one-tenth wavelength rule at 28 GHz, the accuracy for numerical dosimetry has been confirmed in [17]. The convolutional perfect matched layer was used for truncating the FDTD simulation domain. Its excellent absorption effectiveness has been confirmed for near field and for evanescent field [45], [46]. The local SAR [5], [6] is defined as

\[
SAR(x, y, z) = \frac{\sigma(x, y, z)}{2\rho(x, y, z)} |E(x, y, z)|^2
\]

where \(E(x, y, z)\) denotes the peak value of the electric field at position \((x, y, z)\), and \(\sigma\) and \(\rho\) represent the conductivity and mass density of the tissue, respectively. The local SAR was evaluated for every voxel in the body model for both 2 GHz and 28 GHz. Then the superposed local SAR for simultaneous exposure to both antennas was obtained by (2) and was then used for computing the temperature rise.

\[
SAR_{\text{total}}(x, y, z) = SAR_{2\text{GHz}}(x, y, z) + SAR_{28\text{GHz}}(x, y, z)
\]

The dielectric properties of tissues were determined using the 4-Cole–Cole dispersion model [47], where the maximum frequency at which the measured data were considered was 20 GHz. Measurements at high frequencies have been conducted and discussed in [48], [49]. The 4-Cole–Cole model for skin tissue in [44] were determined by

![Figure 1. Bird's-eye view of the (a) seven-layer cubic head model, (b) side head model captured from a realistic head model.](image-url)
measurement using dielectric probe attaching to human skin surface. In [47], the dielectric property and loss factor were distinguished for epidermis and dermis. The results have shown that the skin dielectric property and loss factor in [44] stay in middle of those measured in [47] for epidermis and dermis. Below 20 GHz, the skin dielectric property and loss factor in [44] differ from those in [47] by 9% and 16%. From the Monte Carlo analysis [47] for various combination of tissue thicknesses, the relative standard deviation in transmittance for exposure from 30 GHz to 1 THz waves is no larger than 2%. The computational results in [46] also showed that the difference between three-layer (skin, subcutaneous fat, muscle) and four-layer (epidermis, dermis, subcutaneous fat, muscle) model is several percent at 30 GHz. Therefore, in this study, the values from [44] were adopted for the electromagnetic modelling, as the epidermis and dermis were not distinguished.

C. THERMAL ANALYSIS
A computational method for the temperature rise similar to that employed in our previous study [50] was adopted. The temperature in the human model was computed by solving a bioheat transfer equation [51]. Potential thermoregulatory changes in the skin blood flow were not considered because they are negligible for local increases in skin temperature (without an increase in core temperature) below 1°C–2°C [52].

The equation, considering heat conduction, blood perfusion, and electromagnetically induced heating (SAR), can be expressed as follows:

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

where \( T \) represents the temperature of the tissue, \( T_b \) the blood temperature, \( C \) the specific heat of the tissue, \( K \) the thermal conductivity of the tissue, \( M \) the metabolic heat generation, \( B \) the term associated with blood perfusion, and \( t \) the time variable. The blood temperature was assumed to be spatiotemporally constant in the tissue because local exposure scenarios were considered, which are insufficient to cause a core temperature rise [52]. Therefore, the blood temperature \( T_b \) in (3) was set constant at 37°C. The boundary condition for (3) is given by

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

where \( H \), \( T_s \), and \( T_e \) denote the heat transfer coefficient, skin temperature, and ambient temperature (independent of the position), respectively. In the frequency range considered herein (>6 GHz), heating is confined to a thin (mm or less) layer near the surface [40], and heat transport occurs mainly via thermal conduction owing to the large temperature gradients near the surface.

Assuming a steady-state condition and neglecting thermoregulation, all terms on the right-hand side of (3) are considered independent of \( t \), and the equation can be expressed as follows:

\[
\nabla \cdot (K(r) \nabla T(r)) + \rho(r)SAR(r) - B(r)T(r) = 0,
\]

where \( T \) denotes the temperature rise. The equation is solved using a finite-difference method accelerated through the geometric multigrid method [17].

Most thermal parameters used in this study are the same as those used in our previous study [53], and they were adapted from [54]. The blood flow in the skin tissue was adapted from [55]. As discussed in [56], the blood flow varies substantially in a shallow region (from the skin surface to 3 mm), but its impact on the steady-state increase in surface temperature is ±15% at frequencies higher than 6 GHz, which is consistent with the Monte–Carlo approach [57].

The validations for both the electromagnetic and thermal computation programs have been confirmed in intercomparision studies led by IEEE IACES Sc6 [48].

E. METRICS FOR EVALUATION
SAR averaged over 10 g of tissue (<6 GHz) and APD averaged over an area of 4 cm² (>6 GHz) are considered as metrics according to the guidelines/standards. For exposure to the inverted-F antenna at 2 GHz, we computed the 10-g cubically averaged SAR following the procedure specified in IEEE C95.3 [ref]. The SAR₁₀g at \((x', y', z')\) with a valid averaging volume was obtained by:

\[
SAR_{10g}(x', y', z') = \frac{\int_{V} \rho(x, y, z) \cdot SAR(x, y, z) dxdydz}{\int_{V} \rho(x, y, z) dxdydz}
\]

where \( V \) is the volume for 10-g tissue in the shape of a cube centered at \((x', y', z')\). The above SAR averaging equation does not apply to voxels which are not the centers of valid averaging volumes. These voxels were assigned the highest averaged SAR₁₀g of the averaging volume in which they are enclosed (see IEEE C95.3 annex E for details).

For exposure to patch array at 28 GHz, the 4-cm² area-averaged APD was obtained by:

\[
APD_{4cm²}(y', z') = \frac{\int_{A} dxdz \int_{0}^{\delta_{max}} \rho(x, y, z) \cdot SAR(x, y, z) dx}{A}
\]

where \( x \) denotes the axis perpendicular to the model surface. APD corresponds to the SAR integrated over the depth direction [5], [6]. \( A \) is the averaging area of 4 cm² centered at \((y', z')\). For both the planar and side head models, the APD were evaluated by integrating over the \( x \) direction as illustrated in Fig. 1. As revealed in [58] that the variations in APD caused by the averaging schemes for nonplanar surface models are marginal at 28 GHz.

The basic restrictions of SAR averaged over 10 g (SAR₁₀g) and APD averaged over 4 cm² (APD₄cm²) are 2 W/kg and 20 W/m², respectively, for general public. For the side head
model, SAR_{10g} was adjusted to 2 W/kg, excluding the pinna. SAR_{10g} in pinna did not exceed the restriction of 4 W/kg.

The face of SAR averaging volume, which is approximately 22 mm × 22 mm, does not match exactly to the averaging area of 4 cm². Thus, the straightforward comparison is difficult. The computed SAR and APD were normalized at the stated limits. According to the international standard/guidelines, SAR and APD should satisfy the following equation:

\[
\frac{\sum_{i=100\text{GHz}}^{6\text{GHz}} \text{SAR}_i}{\text{SAR}_L} + \frac{\sum_{i=6\text{GHz}}^{100\text{GHz}} \text{APD}_i}{\text{APD}_L} \leq 1, \tag{8}
\]

where SAR\textsubscript{i} and APD\textsubscript{i} represent the local SAR_{10g} and APD_{4cm²} at frequency \textit{i}. SAR\textsubscript{L} and APD\textsubscript{L} denote the basic limits/dosimetric reference limits (permissible internal physical quantities) recommended in the guidelines/standards. Equation (8) must be satisfied for every position in the human body. However, as seen from the equations (6) and (7), the SAR_{10g} is three-dimensional, while APD_{4cm²} is two-dimensional. In addition, the skin surface voxels were assigned the highest averaged SAR_{10g} of the averaging volume in which they are enclosed. This nonlinear process results in a boarder and higher distribution of SAR_{10g} on the model surface, compared to the simple averaging method adopted for APD_{4cm²}. As a conservative approach, equation (8) was evaluated on the surface voxels (i.e., \(x' = 0\)).

**F. EXPOSURE SCENARIOS**

Fig. 2 shows the antennas considered in this study, which included a four-element patch antenna array operated at 28 GHz and an inverted-F antenna at 2 GHz. The antennas were excited by harmonic sources. The distance between the head model and antenna/substrate was 5 or 15 mm. The separation distance of 5 mm corresponds to a case that the body is in close proximity to the radiation sources. This scenario (i), the SAR and power density distribution are rather localized. The separation distance of 15 mm corresponds to a case that the body is more confined in the regions under the antennas, thus less superposition effect can be expected. For the side head model, because of the presence of pinna, which is commonly excluded from the SAR and temperature rise assessments, the smallest distance between the antenna and head surface (excluding pinna) is 14.5 mm and the smallest distance between the antenna and head surface (including pinna) is smaller than 1 mm. Therefore, only the distance of 15 mm was considered for the side head model.

We considered two exposure scenarios. In exposure scenario (i), the separation between the patch array and inverted-F antenna was varied to assess their superposition effect on the temperature rise in the head model. The separation between the patch array and inverted-F antenna (\(h\) in Fig. 2) was in the range of 20–120 mm in 10-mm increments. The device and the inverted-F antenna positions were fixed, and the patch array position was varied. In scenario (ii), the patch was implemented on the opposite side from the head model, assuming that the device was generally used.
III. COMPUTATIONAL RESULTS

A. FREE-SPACE POWER DENSITY EMITTED FROM HANDSET

The antenna characteristics of the inverted-F antenna at 2 GHz and the four-element patch antenna array at 28 GHz without the head model were first confirmed. The antenna and array positions for each exposure are shown in Fig. 2. The return losses of the antennas were less than $-10 \, \text{dB}$ for different separations between them.

Fig. 3 shows the distribution of free-space power density emitted from the inverted-F antenna at 2 GHz and the four-element patch antenna array at 28 GHz for different separation lengths. The output power of the inverted-F antenna and patch array were normalized such that $\text{SAR}_{10g} = 2 \, \text{W/kg}$ and peak $\text{APD}_{4\text{cm}} = 20 \, \text{W/m}^2$ for the cubic head model located 5 mm from the antenna.

As shown in Fig. 3, the power density from the patch antenna array was strong in the same direction as the substrate. A part of the radiated field exposed to the patch antenna diffracted to the opposite side of the substrate with a

![Image](https://example.com/image3)

FIGURE 3. Free-space power density from patch antenna array and inverted-F antenna for their different separation: (a) $h=120 \, \text{mm}$, (b) $h=60 \, \text{mm}$.

![Image](https://example.com/image4)

FIGURE 4. Power loss distributions in the multi-layer cubic head model for (a) inverted-F antenna, (b) patch array ($h=40 \, \text{mm}$). Upper and lower figures are distributions for a 5-mm and 15-mm distance between antenna and head surface.

![Image](https://example.com/image5)

FIGURE 5. Temperature rise distributions in the multi-layer cubic head model for (a) inverted-F antenna and (b) patch antenna array ($h=40 \, \text{mm}$).

![Image](https://example.com/image6)

FIGURE 6. (a) Distribution of power loss and (b) temperature rise for the superposition from patch antenna array and inverted-F antenna, at $h=40 \, \text{mm}$.

| Distance $d$ [mm] | Cubic Head Model | Side Head Model |
|------------------|------------------|-----------------|
|                  | 5                | 15              | 15              |
| Output power of the inverted-F antenna [W] | 0.171 | 0.776 | 0.735 |
| Output power of the patch antenna array [W] | $h=20 \, \text{mm}$ | 0.014 | 0.020 | 0.060 |
|                  | $h=30 \, \text{mm}$ | 0.014 | 0.020 | 0.045 |
|                  | $h=40 \, \text{mm}$ | 0.014 | 0.019 | 0.035 |
|                  | $h=50 \, \text{mm}$ | 0.014 | 0.020 | 0.031 |
|                  | $h=60 \, \text{mm}$ | 0.014 | 0.019 | 0.027 |
|                  | $h=70 \, \text{mm}$ | 0.014 | 0.019 | 0.032 |
|                  | $h=80 \, \text{mm}$ | 0.014 | 0.019 | 0.030 |
|                  | $h=90 \, \text{mm}$ | 0.014 | 0.019 | 0.024 |
|                  | $h=100 \, \text{mm}$ | 0.014 | 0.019 | 0.034 |
|                  | $h=110 \, \text{mm}$ | 0.014 | 0.019 | 0.032 |
|                  | $h=120 \, \text{mm}$ | 0.015 | 0.022 | 0.024 |
large separation between the two antennas ($h = 120$ mm). The inverted-F antenna radiated electromagnetic waves on both sides of the substrate because the antenna was located at the bottom of the substrate.

The far-field patterns of the antenna and array are not shown here because they are irrelevant to near-field coupling. For different phase shifts between the array elements, the distributions differ remarkably, but the highest field strength is obtained for the normal incidence or no phase difference between the array elements partly because of the smallest distance between the source and illuminated position [46]. Therefore, only normal incidence was considered.

**B. POWER DEPOSITION AND TEMPERATURE RISE FROM EXPOSURE TO SINGLE ANTENNA**

Fig. 4 shows the power loss distributions in the cubic head model for the inverted-F antenna and patch antenna array. The output power of each antenna was adjusted such that the peak SAR$_{10g} = 2$ W/kg and peak APD$_{4cm^2} = 20$ W/m$^2$, which are the limits according to the international guidelines and standards. For different distances ($d = 5$ and 15 mm), the output power corresponding to the permissible SAR (2 W/kg) and APD (20 W/m$^2$ for the averaged area of 4 cm$^2$) were computed and are listed in Table I. For the power deposition from the exposure to the inverted-F antenna at 2 GHz (Fig. 4a), the peak SAR values were observed in the muscle, which was located a few millimeters below the surface. For the patch antenna array, the power deposition distribution was more localized because a beam was formed (Fig. 4b). The beamwidth, which is defined as $1/e$ of the peak Poynting vector strength, of the patch array was 2.11 and 2.64 cm$^2$ at the distances of 5 and 15 mm, respectively.

Fig. 5 shows the distribution of temperature rise in the cubic head model exposed to each antenna. The temperature-rise distributions were broader and smoother than power loss distributions because of the heat diffusion in biological tissues. The resultant peak rise in surface temperature for the inverted-F antenna and patch array was 0.37°C and 0.43°C, respectively, at $d = 5$ mm and 0.34°C and 0.43°C, respectively, at $d = 15$ mm.

**C. POWER DEPOSITION AND TEMPERATURE RISE FROM EXPOSURE TO BOTH ANTENNAS**

For exposure scenario (i), the position of the patch antenna array was varied to examine the superposition effect of SAR and APD. The output power of each antenna was adjusted such that the peak SAR$_{10g} = 2$ W/kg and peak APD$_{4cm^2} = 20$ W/m$^2$, as listed in Table I. Notably, the intensity from two antennas does not satisfy the basic restrictions for simultaneous exposure to multiple frequency fields in the guidelines and standards. Fig. 6 shows the distributions of power loss and temperature rise in the cubic head model for both the antennas at the separation distance $h = 40$ mm. As shown in Fig. 6a, the power deposition distribution on the skin surface was localized owing to the exposure from the patch antenna array. The peak temperature rise was observed on the skin. The temperature-rise distributions were broader and smoother than the power density distributions (Fig. 6b). By comparing with the distributions from individual antennas, the power absorption and temperature rise from the patch array were dominant in the skin. The power loss density in the skin from the patch array is several times higher than that from the inverted-F antenna. Note that the APD and SAR were normalized to their corresponding BR limits. The SAR distribution at $d = 15$ mm is broader than that at $d = 5$ mm.
exposure was less than 15% at separation distances greater than 5-mm antenna-model separation, the effect of simultaneous exposure to the patch antenna array only. For the scenarios of rise relative to the peak temperature rise caused by an antenna was adjusted such that the resultant SAR or APD to the basic were varied according to the simultaneous exposure at multiple frequencies at \( h = 20 \text{ mm} \). Based on Fig. 7, \( h = 20 \text{ mm} \) was considered where the largest superposition effect was observed. As shown in Fig. 9, the peak temperature rise was highest when the ratio of APD was 1, suggesting that the skin temperature rise caused by the patch array antenna was dominant. The minimal peak temperature rise was observed at \( \text{APD/\text{APD}_b} = 0.3 \) for 5-mm body-antenna separation distance and \( \text{APD/\text{APD}_b} = 0.1 \) for the 15- and 25-mm separation distances.

E. TEMPERATURE RISE TO SATISFY THE BASIC RESTRICTIONS FOR SIMULTANEOUS EXPOSURE

Assuming the worst case where (8) is satisfied, the ratio of the computed SAR or APD to the basic were varied according to the simultaneous exposure at multiple frequencies at \( h = 20 \text{ mm} \). Based on Fig. 7, \( h = 20 \text{ mm} \) was considered where the largest superposition effect was observed. As shown in Fig. 9, the peak temperature rise was highest when the ratio of APD was 1, suggesting that the skin temperature rise caused by the patch array antenna was dominant. The minimal peak temperature rise was observed at \( \text{APD/\text{APD}_b} = 0.3 \) for 5-mm body-antenna separation distance and \( \text{APD/\text{APD}_b} = 0.1 \) for the 15- and 25-mm separation distances.

F. EVALUATION SIMULATING THE GENERAL USAGE OF A HANDSET

Fig. 10 shows the power loss distributions for the two antennas at the separation distance \( h = 120 \text{ mm} \), where the highest radiation from the patch array was observed on the opposite side of the substrate due to diffraction. As shown in Fig. 10, the power loss caused by the patch antenna array was comparable to that by the inverted-F antenna because of the shallow penetration depth. The temperature-rise distributions for the patch antenna array and inverted-F antenna did not overlap; thus, (8) was not applied, and a separate consideration was enough.

When using a mobile terminal, the radiation from the patch antenna array is usually directed to the opposite of a human for antenna efficiency. Fig. 11 shows the temperature-rise distributions when directing the radiation of the patch antenna opposite to the cube and toward the cubic head model. The separation distance between the two antennas was chosen as \( h = 40 \text{ mm} \). When the patch is implemented on the opposite side of substrate from the model, the distribution of superposition was in good agreement with that of the single exposure from the inverted-F antenna. The difference in the superposed temperature rise relative to that of the inverted-F antenna was less than 0.01%.

IV. DISCUSSION AND CONCLUDING REMARKS

This study evaluated the temperature rise from simultaneous exposure to two sources, i.e., the antenna and array operated at different frequencies (2 and 28 GHz). One of the difficulties in the evaluation was that the metrics recommended in the international guidelines and standards differ above and below the frequency of 6 GHz. However, the assessment of the simultaneous exposure above and below 6 GHz was set conservatively, and a more realistic
assessment may provide additional insight into the guidelines. To fill out the gap and considering the consistency between the exposure and product standards, SAR and APD and the resultant temperature rise were evaluated herein.

The computational results showed higher superposition effect for the temperature rise than for the SAR or APD distributions. This could be attributed to the heat diffusion length in the biological tissue. From the computations for the two antennas adopted in this study, the effect of the superposition was generally below 15% at h > 50 mm for a 5 mm antenna body separation. For the side head model, enhancement of more than 15% was observed at 80 mm, which could be attributed to the effect of the pinna. The temperature in the pinna is greatly affected by its shape, which varies with individuals and may be pressed by the handset during usage. Further discussion on the effect of pinna on SAR and temperature can be found in previous studies [53][59]. Although not discussed substantially for oblique incidence or different phase differences of array elements, the same tendency is expected [46].

We also evaluated the temperature rise with various ratios of SAR or APD to the basic restrictions to satisfy the guidelines and standards for simultaneous exposure at multiple frequencies. From the linearity of the steady-state bioheat equation, and the conservativeness of the superposition equation for \( \text{SAR}_{10g}/\text{APD}_{10g} \), the temperature rise at the skin surface was below 0.5°C and was lower than the maxima resulted from SAR/APD from a single antenna, also considering the processing method for SAR/10g at surface voxels. Notably, ICNIRP set the APD limit corresponding to the skin temperature rise at 0.5°C for general public. IEEE states a temperature rise of 2°C–3°C for a controlled environment. The least temperature rise was observed at the ratio of 0.3–0.4 for a 5-mm separation distance considered in this study, which appeared by the balance of the SAR and APD. Also note that the SAR/10g is three-dimensional while APD/10g is two-dimensional, in this study, we superposed the two metrics on the surface voxels only, this is conservative because the SAR/10g decreases with the depth at 2 GHz. The abovementioned marginal enhancement is partly attributed to the depth where the maximum temperature rise was observed. At 2 and 28 GHz, the maximum temperature rise was observed in the muscle and at the skin surface, respectively. For the combination considered herein, the surface temperature rise was significant because SAR is a metric to prevent excessive temperature rise on the skin and inner tissue (e.g., brain), whereas the skin is only above 6 GHz. The revised IEEE standard and ICNIRP guidelines are based on the thermal model to prevent excessive temperature rise in different tissues. Thus, the limit of 6–30 GHz would be set conservatively [27], [39]. Thus, the resultant temperature rise should be comparable to each other. Therefore, the equation for compliance assessment was demonstrated to be conservative, and the distribution of power deposition was identical. Thus, as expected, the exposure only at 2 or 28 GHz provided higher rises in the skin temperature.

In practice, the compliance for 2-GHz antenna and 28-GHz array separately would be enough although further investigation is needed when the antennas, or more precisely, the power deposition distributions, are closer to each other. The conservatives of superposition is modest (below 38%), which may not result in overconservativeness for the use of multiple frequencies simultaneously.

Future studies may include simultaneous exposures to near- and far-field sources and brief exposures to electromagnetic energy at different frequencies to confirm new description in the guidelines and standard.

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