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Published in:
IEEE Transactions on Electromagnetic Compatibility

DOI:
[10.1109/TEMC.2021.3098594](https://doi.org/10.1109/TEMC.2021.3098594)

Published: 01/10/2021

Document Version
Peer reviewed version

Please cite the original version:
Diao, Y., Li, K., Sasaki, K., Koder, S., Laakso, I., Hajj, W. E., & 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 Transactions on Electromagnetic Compatibility*, 63(5), 1709-1716.
<https://doi.org/10.1109/TEMC.2021.3098594>

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Effect of Incidence Angle on the Spatial-Average of Incident Power Density Definition to Correlate Skin Temperature Rise for Millimeter Wave Exposures

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Abstract—This paper reports on an intercomparison study on the effect of the incidence angle on the spatial average of incident power density (PD) and resultant temperature rise using computational and thermographic measurement approaches. Two definitions of the spatial average of incident PD—the peak spatial-average normal component of the Poynting vector and peak spatial-average norm of the Poynting vector—were compared. First, an intercomparison of incident PD and temperature rise in a layered skin model was conducted for a 4×4 dipole array antenna. The variations caused by antenna type, antenna-body distance, and skin model to these definitions were then discussed. The results revealed that both definitions are in good agreement and correlate with the peak temperature rise for small or moderate incidence angles. The heating factor was enhanced for transverse-magnetic-like polarized waves for peak spatial-average normal component of the Poynting vector for large-angle incidences because of the Brewster effect. The normal incidence scenario was confirmed to be essential for considering the peak skin temperature rise.

Index Terms—millimeter wave exposure, electromagnetic safety, standardization, skin model, temperature rise, incident power density.

I. INTRODUCTION

TWO international guidelines and standard for human protection from electromagnetic fields mentioned in the World Health Organization—ICNIRP Guidelines (100 kHz–300 GHz) [1] and IEEE International Committee on Electromagnetic Safety (ICES) C95.1 standard [2]—were revised in 2020 and 2019, respectively. These guidelines and standard prescribe two-tier approaches to ensure protection. First, the basic restriction (BR) [1] or dosimetric reference limit

(DRL) [2] (hereafter BR is used as IEEE C95.1-2005 [3] also used this expression), which is internal physical quantity, was set. These limits were derived based on the substantiated adverse health effects considering safety factors [2] or reduction factors [1]. The reference level (RL) [1] or exposure reference level (ERL) [2] (hereafter RL is used to refer to ERL), which is an external physical quantity, was derived based on the BR in a conservative manner.

In the revised guidelines and standard, primary changes exist particularly at frequencies above 6 GHz [4]. First, the spatial average of absorbed or epithelial power density (PD), which is a surrogate of skin temperature rise, was introduced as a physical quantity for BR. The absorbed or epithelial PD is the power per unit area deposited in biological tissues. In [1], the BR was derived considering an operational temperature threshold of 5 °C for the skin. Then a reduction factor of 2 was applied for occupational exposure corresponding to a skin temperature rise of 2.5 °C. In [2], the skin temperature rise in a controlled environment is suggested to be 2–3 °C based on thermal modeling. Then, the spatial average of incident PD, corresponding to absorbed or epithelial PD, was derived in a conservative manner.

Numerous studies have been conducted on the electromagnetic power absorption and temperature rise in body models for exposures above 6 GHz [5]–[15]. In [7], [8], plane-wave exposure scenarios were considered for a one-dimensional model. The effect of the plane-wave incidence angle on the transmittance [9] and temperature rise [10] has been studied, the dependence of the transmittance on the incidence angle differs for transverse electric (TE) and transverse magnetic (TM) waves owing to Brewster's angle effect. In [11]–[15], exposures to electromagnetic waves from

Manuscript received xxxx; revised xxxx; acceptedxxxx. Date of publication xxxx; date of current version xxxx. (Corresponding author: Yinliang Diao)

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the antennas were considered. [12] suggested that a 4-cm² averaged incident PD correlates well with skin temperature rise for rather uniform PD distributions. The contribution of reactive near field to power deposition in tissues is small in millimeter wave bands when the antenna-body separation is larger than approximately one wavelength [14]. However, the interaction between the antenna and body cannot always be neglected, particularly for array antennas [15]. Moreover, the effect of incidence angle has not been thoroughly studied.

In the international exposure guidelines and standard [1], [2] the incident PD is the electromagnetic power per unit area crossing a surface of interest, this definition is given in a rather theoretical manner, and does not include information on the exposure assessment methods. However, with the development of product safety standards, how to define the spatial average of incident PD considering practical measurement procedures should be addressed. The limits for local exposures are designed to prevent an excess surface temperature rise for frequencies above 6 GHz; thus, the resultant temperature rise should be considered to set the definition of spatial average of incident PD, which is calculated based on Poynting vector. Further, whether spatial average of the norm or normal component of incident Poynting vector (see Section II.D) corresponding to the surface of the exposed body model is a more appropriate surrogate for skin temperature rise in realistic assessments should be addressed, as discussed in the joint meeting of IEC Technical Committee (TC) 106 and IEEE ICES TC34 on product safety. However, it is out of the scope to evaluate the temperature rise in the product safety standardization activity, unlike the exposure safety standard, and thus additional investigation is needed.

In [16], the spatial average of normal component of the Poynting vector correlates well with the surface skin temperature rise for small incidence angles (<30°); however, only one-dimensional dipole array antennas and a homogenous cubic model were considered. In particular, no intercomparison study has been conducted to evaluate these metrics. Therefore, a new working group 5 under Subcommittee 6 of IEEE ICES TC95 was established to clarify these aspects. First objective of this working group was to conduct an intercomparison between the research organizations. The diversities in different models, parameters, and exposure scenarios allow for the statistical analysis of the results. Following the efforts, original three groups and one new group participated in the discussion on the effect of incidence angle. This paper reports on the effect of the incidence angle on the spatial-average PD (*sPD*) and resultant temperature rise using both computational and thermographic measurement approaches.

II. COMPUTATIONAL MODELS AND METHODS

A. Antenna and Skin Model

Three planar skin models were employed in this study. Variations in the inner tissue composition are shown in Fig. 1 (a). The size of the skin model was 160 × 80 × 20 mm, as shown in Fig. 1 (b). Considering the shallow penetration depth at 30 GHz, the effect of model curvature on *HF* results was marginal

Fig. 1. (a) Three skin models with different tissue compositions. (b) Exposure condition.

TABLE I
TISSUE THICKNESSES (*T*) AND THERMAL PROPERTIES (DEFINED IN SECTION II.C) FOR DIFFERENT SKIN MODELS.

Model	Tissue	<i>t</i> [mm]	<i>k</i> [W/(m·°C)]	<i>B</i> [W/(m ³ ·°C)]	<i>ρ</i> [kg/m ³]
1-layer	Skin	20.0	0.37	2230	1100
3-layer	Skin	1.5	0.37	7441	1109
	Fat	4	0.21	1903	911
	Muscle	14.5	0.49	2691	1090
4-layer	Epidermis	0.2	0.45	0	1109
	Dermis	1.0	0.42	9100	1109
	Fat	3.8	0.25	1700	911
	Muscle	15.0	0.5	2700	1090

[17], only planar models were considered in this study. The dielectric properties of the tissues were obtained using a four-Cole–Cole dispersion model [18]. The thicknesses and thermal properties of each tissue in the models are listed in Table I.

Five array antennas—including 4 × 1, 8 × 1, 4 × 2, and 4 × 4 half-wave dipole array antennas as well as a 4 × 4 patch array antenna—were adopted as the radiation sources and were placed at a distance *d* from the skin surface, as shown in Fig. 1 (b). Three antenna-body distances, that is, *d* = 5, 10, and 30 mm, were considered. The working frequency was set to 30 GHz. The dipole array element was modeled as an infinitely thin wire with a length of 4.25 mm. The separation between array elements *δ* is 5 mm. The parameters for the 4 × 4 patch array are shown in Fig. 2.

For TE-like polarization, the dipoles were aligned along the *x*-axis (as shown in Fig. 1 (b)), and each array element was excited by a delta-gap source with the same amplitudes. The incident angle to the body surface is equivalent to the beam steering angle of the array antenna, as the surfaces of antenna and body are parallel. The phase of excited signal of each element was determined by:

$$\varphi_i = -(i - 1)k\delta \sin \phi \quad (1)$$

Fig. 2. Geometry of 4 × 4 patch array antenna.

where φ , k , δ , and ϕ represent the initial phase, wave number, antenna separation, and beam angle, respectively, and i represents the row number (in the y -direction) in the two-dimensional array. Array elements in the same row were fed with the same phase. For the TM-like polarization, the array antennas were rotated 90° about the z -axis. The phases were determined using (1). Beam directions from 0° to 60° , at 15° intervals, were considered.

Another source commonly used for exposure assessment at frequencies above 6 GHz is the plane wave, which corresponds to a far-field scenario. The plane wave source was also adopted. The variations in the exposure settings are summarized in Table II. Among these variations, the exposure scenario defined by the bold parameters in Table II was selected for the comparison of the computational results across research groups.

B. Electromagnetic Field Computation

For the electromagnetic field computations, the finite-difference time-domain (FDTD) method was used because of its capability to handle inhomogeneous media such as the human body. Perfect matched layer boundary condition was adopted to truncate the simulation domain, simulating free space [19]. The spatial resolution for the simulation was 0.25 mm. The computations using the FDTD method were carried out using (A) the XFDTD [20], in addition to the in-house code by each research group of (B) National Institute of Information and Communications Technology (NICT), (C) Nagoya Institute of Technology (NITech), and (D) South China Agricultural University (SCAU).

C. Heat Transfer Computation

The Pennes bioheat equation [21] was employed to evaluate the temperature rise in body models, which is as follows:

$$\nabla \cdot (k \nabla T) + \rho \text{SAR} + M - B(T - T_b) = c\rho \frac{\partial T}{\partial t} \quad (2)$$

where c is the specific heat of the tissue [J/(kg $\cdot^\circ\text{C}$)], k [W/(m $\cdot^\circ\text{C}$)] is the thermal conductivity, B [W/(m $\cdot^\circ\text{C}$)] is a coefficient related to the blood perfusion rate, M [W/m 3] is the rate of metabolic heat generation, T_b is the temperature of the perfusing blood, ρ [kg/m 3] is the tissue mass density, and SAR [W/kg] is the specific absorption rate. The boundary condition for (2) is expressed as follows:

$$k \frac{\partial T}{\partial n} + H(T_s - T_e) = 0 \quad (3)$$

where H [W/(m $\cdot^\circ\text{C}$)] represents the heat transfer coefficient

from the skin to the surrounding air, T_s and T_e are surface and ambient temperatures, respectively. The variable n denotes the axis perpendicular to model surface. A lower heat transfer coefficient results in a slightly higher temperature increase. In this study, H was set as 8 W/(m $\cdot^\circ\text{C}$), which is consistent with the value used in several previous studies [22]–[24]; H was within the range of values used in [25] under different air velocities. The thermal parameters are listed in Table I.

The bioheat equation is linear in the thermally steady state if the temperature increase is not sufficiently high to activate the thermoregulatory system [26]. Assuming a steady state and neglecting metabolic heat generation, (2) can be modified as follows:

$$\nabla \cdot (k \nabla \Delta T) + \rho \text{SAR} - B \Delta T = 0 \quad (4)$$

where ΔT is the temperature rise. The temperature rise was computed by each research group separately, forming four datasets for the intercomparison: (A) a program using the geometric multigrid method with successive over-relaxation developed at Aalto University was used to solve the steady-state bioheat equation; (B) and (C) the FDTD method was used by the groups from NITech and NICT, the temperature rise was obtained by subtracting the temperature computed without EM power deposition (i.e., SAR=0 W/kg); and (D) the Jacobi iterative method with GPU acceleration was used at SCAU for solving (4). For plane incident waves, the results were obtained using analytical formulae for temperature rise, which were derived from the one-dimensional baseline bioheat equation for obliquely incident TE and TM plane waves [10].

D. Postprocessing

The incident PD on the evaluation plane at distance d from the array antenna was obtained. Two definitions of sPD for time-harmonic electromagnetic fields were examined without the presence of the human body: sPD_n is the spatial average of the normal component of the time-averaged Poynting vector, as defined by (5); sPD_{tot} is the spatial average of the norm of the Poynting vector, as defined by (6), for which all three components of the Poynting vector are considered.

$$sPD_n = \frac{1}{2A} \iint_A \text{Re}[\mathbf{E} \times \mathbf{H}^*] \cdot \mathbf{n} dA \quad (5)$$

$$sPD_{\text{tot}} = \frac{1}{2A} \iint_A \|\text{Re}[\mathbf{E} \times \mathbf{H}^*]\| dA \quad (6)$$

In (5) and (6), $\mathbf{E}$ and $\mathbf{H}$ denote the complex electric field and magnetic field vectors, $*$ denotes the complex conjugate, A is the averaging area, which is taken as 4 cm 2 , as suggested in [1], [2], and $\mathbf{n}$ is the unit vector normal to the evaluation plane. The time domain electric and magnetic field components on the observation plane were first obtained from FDTD simulations, and then transformed to the $\mathbf{E}$ and $\mathbf{H}$ vectors in frequency domain for computing PD using (5) and (6). Then, the heating factors (HF s), which are defined by (7) and (8), were compared.

$$HF_n = p\Delta T / (psPD_n) \quad (7)$$

$$HF_{\text{tot}} = p\Delta T / (psPD_{\text{tot}}) \quad (8)$$

where $p\Delta T$ is the spatial-peak value of steady-state temperature

TABLE II
SUMMARY OF PARAMETER VARIATIONS, d IS DISTANCE FROM RADIATION SOURCES TO BODY SURFACE

d [mm]	Model	Source
5	1-layer	4×1 dipole array
10	3-layer	8×1 dipole array
30	4-layer	4×2 dipole array
		4×4 dipole array
		4×4 patch array
		Plane wave

Fig. 3. Distributions of normalized spatial-average PD_n (upper), PD_{tot} (middle), and temperature rise (lower) on the observation plane for (a) TE-like and (b) TM-like polarized waves from the 4×4 half-wave dipole array at 30 GHz. The regions labeled by the white squares correspond to the size of the dipole array antenna and are magnified to show the orientations of antennas for TE and TM-like polarizations. The distance between antenna and observation plane is 30 mm.

rise at the skin surface, $psPD$ is the spatial-peak of sPD . Subscripts n and tot denote the normal component and norm of the Poynting vector, respectively. The relative standard deviation (RSD), which is defined as the ratio of standard deviation to the mean of HF s obtained from the four sets of results, was computed for intercomparison.

III. COMPUTATIONAL RESULTS AND DISCUSSION

A. Intercomparison

1) Distributions of sPD and ΔT

Figs. 3 (a) and (b) show the computed distributions of the normalized sPD_n and sPD_{tot} on the evaluation plane ($d=30$ mm), and the ΔT on the body model surface owing to the exposure to TE- and TM-like polarized waves generated by the 4×4 dipole array antenna. The sPD and ΔT distributions calculated by all four groups are almost identical; to reduce the redundancy, the results obtained from one group are shown here. Notably, the incidence angle is defined in the far-field region. The incidence angle, if defined in terms of the hotspot on the observation plane in the near-field region, may differ slightly from the far-field definitions. However, the difference in the incidence angles between the two definitions is rather small, generally less than approximately 5° in the considered cases. The exposed area increases with the incidence angle for both TE- and TM-like polarized waves. The differences between the sPD_n and sPD_{tot} distributions were rather small, with slightly noticeable

differences for the large-angle incidence cases.

2) Heating Factors

The heating factors, HF_n and HF_{tot} , for the three-layer skin model for TE-like polarized incident waves at different incidence angles are shown in Figs. 4 (a) and (b), respectively. Those for TM-like polarized waves are shown in Figs. 4 (c) and (d). For the considered incidence angles, the highest HF_n and HF_{tot} appeared for normal incidence cases ($\phi = 0^\circ$), and the HF s showed a general decreasing trend with increasing incidence angle. HF_n for TM-like cases slightly rises when the incidence angle exceeds 45° . This phenomenon is attributable to the Brewster's angle effect. In general, the variations in HF_n with the incidence angle are lower than those for HF_{tot} .

3) Relative Difference from Each Group

The RSD values for HF_n and HF_{tot} obtained by each research group for varying incidence angles are summarized in Table III. The RSDs were lower than about 5%, indicating good agreement across the four sets of results. The differences observed are considerable smaller than those observed previously in peak spatial-average SAR in an intercomparison study [27], where complex head models were adopted.

B. Variability of Radiation Source

Variabilities caused by the different sources are shown in Fig. 5, for a 30 mm distance between antenna and body surface. The HF s for incident plane waves, shown as black curves in Fig. 5, were calculated using an analytical formula of the bioheat equation [10]. As shown, the highest HF s appear for the normal incidence cases for the 4×4 dipole and 4×4 patch arrays, whose beam areas are the smallest. For relatively larger beam areas generated by the 4×1 , 8×1 , and 4×2 dipole array antennas, the HF s are comparable to those of the plane-wave cases. For the HF_n of incident TM plane waves, the Brewster effect causes an increase in HF s with an increasing angle of incidence up to the maximum transmittance angle [10]. Fig. 6 shows the boxplots for HF_n and HF_{tot} for different array antennas and incidence angles. Narrower interquartile ranges are observed for HF_n compared with HF_{tot} suggesting that HF_n is less dependent on the incidence angle, at least for the

TABLE III
RELATIVE STANDARD DEVIATIONS IN HEATING FACTORS FOR DIFFERENT RESEARCH GROUPS

Incidence Angle [$^\circ$]	TE		TM	
	HF_n	HF_{tot}	HF_n	HF_{tot}
0	3.04%	3.05%	3.03%	3.04%
15	2.71%	2.05%	3.42%	3.25%
30	2.88%	2.90%	3.94%	3.76%
45	2.65%	2.99%	3.13%	2.88%
60	4.55%	5.06%	4.04%	3.86%

simulated cases. The distance between the exposed area of the model surface and the antenna center becomes quite large with an increase in the incidence angle. Moreover, for the array antennas considered in this study, incidence angles larger than 60° on the body surface are difficult to achieve, unless the skin model is rotated as in [16]. However, in such situations, the distance between antenna and illuminated area of body surface becomes considerably larger than the normal antenna-body distance, where a high antenna output power is required to generate the corresponding free-space PD; thus, normal incidence is crucial for considering the temperature rise.

C. Variability of Skin Model

In the joint study of the working group, several skin models with different tissue compositions have been adopted by research groups. A previous study [25] investigated the variabilities caused by the changes in the thickness of tissues in a multi-layer model via the Monte Carlo method. Here, the discrepancies caused by various skin models with different thermal parameters were computed. The radiation source was selected as a 4×4 dipole array antenna.

Fig. 4. (a) HF_n and (b) HF_{tot} for TE-like exposure cases; (c) HF_n and (d) HF_{tot} for TM-like exposure cases by different research groups at 30 GHz. A, B, C, D correspond to the different research groups that performed the simulations as part of Subcommittee 6 of IEEE ICES TC95.

The results are shown in Fig. 7. The HFs calculated for the three models with their individual thermal parameters are in good agreement; the highest RSD is 3%, which appears for normal incidence ($\phi = 0^\circ$). The RSD in the HFs decreases with an increasing incidence angle. At $\phi = 60^\circ$, the RSDs in the HFs were less than 1.2%. As concluded in [28], the heat transfer coefficient is the most significant parameter affecting the surface temperature rise. The Monte Carlo analyses demonstrate that the variations in thickness of subcutaneous tissue layers among different individuals contributed more to

Fig. 5. (a) HF_n and (b) HF_{tot} for TE-like exposure cases; (c) HF_n and (d) HF_{tot} for TM-like exposure cases by different array antennas at 30 GHz. Black curves are results for obliquely incident plane waves calculated by an analytical formula [10]. The antenna-body distance is 30 mm.

Fig. 6. Boxplots of HF_n and HF_{tot} for different array antennas and incidence angles at 30 GHz. The antenna-body distance is 30 mm.

variability in the calculated steady-state temperature increases than the uncertainties of dielectric properties [25]. This is reasonable because most of the power is absorbed around the human body surface, and the subcutaneous tissue behaves as a layer of thermal insulation for heat conduction to deeper tissues [8]. For the one-layer skin model, the adopted blood perfusion rate is lower than those for skin or dermis used for the three-layer and four-layer models, as summarized in Table I. If the same blood perfusion rate for skin from the three-layer model is used for the one-layer model, the surface temperature rise would decrease by approximately 20–25%.

D. Variability of Antenna-Body Distance

This subsection discusses the effect of the antenna-body distance on the dependence of the HF s on the incidence angle. A three-layer skin model was adopted for the assessments. Three antenna-body distances of 5, 10, and 30 mm were considered. The 4×1 , 4×4 dipole arrays and plane waves were used as radiation sources. The results are presented in Fig. 8. As shown, the highest HF s tend to appear for normal incidence cases where the difference between HF_n and HF_{tot} is marginal,

Fig. 7. (a) HF_n and (b) HF_{tot} for TE-like exposure cases; (c) HF_n and (d) HF_{tot} for TM-like exposure cases for different skin models at 30 GHz. The antenna-body distance is 30 mm.

with the exception of the 4×1 array antenna when $d = 5$ mm and 10 mm. The HF s for $d = 30$ mm are all below 0.02 $^{\circ}\text{C}/(\text{W}/\text{m}^2)$. For both antennas, as d decreases, HF s increase.

The dependencies of the HF s corresponding to the beam areas are shown in Fig. 9. The beam area here was defined as the area where the PD is larger than $1/e$ of the maximum [15]. High HF s were primarily associated with small beam areas. The HF s become stable when the areas are larger than several square centimeters. The vertical range of the HF was narrower for HF_n than for HF_{tot} . For $d = 30$ mm, the beam area generally increases with the incidence angle. For small-angle incidence cases at $d = 10$ and 30 mm, the beam areas for the 4×4 array are all smaller than those for the 4×1 array. In such cases, compared with the 4×1 array, the 4×4 array, with a narrower beam area, yields higher HF s. An averaging area of 1 cm^2 was also specified in [1]. When $d = 10$ mm and $\phi \leq 30^{\circ}$ for the 4×4 array, the peak 1-cm^2 averaged PDs slightly exceed twice those averaged over 4 cm^2 . If defined using 1-cm^2 averaged PD, the HF s would be scaled down; however, their incident-angle-dependence tendencies did not vary. The effect of the averaging area is beyond the scope of this study; nevertheless, defining an averaging area to cover all nonuniform exposure cases

Fig. 8. (a) HF_n and (b) HF_{tot} for TE-like exposure cases; (c) HF_n and (d) HF_{tot} for TM-like exposure cases for different antenna-body distances at 30 GHz.

Fig. 9. (a) HF_n for 4×4 dipole array, (b) HF_{tot} for 4×4 dipole array, (c) HF_n for 4×1 dipole array, and (d) HF_{tot} for 4×1 dipole array, for different beam areas at 30 GHz.

(particularly extremely localized exposures) is difficult or impractical, as concluded by [15]. A rough definition of the reactive near-field boundary for these antennas is $d = 10$ mm (one wavelength) [29]. Therefore, rather complicated distributions of the scatter plots were observed for $d = 5$ mm, where the radiation beam was not formed. When the skin model is in close proximity to the antennas, strong coupling between the antenna and body may notably alter the antenna performance. Moreover, defining the incidence angle in this region is difficult. Thus, there might be limitations in linking the free-space spatial average of incident PD with the temperature rise in the human body in the reactive near-field region of an antenna.

IV. THERMOGRAPHIC MEASUREMENT

The HF s were also evaluated by thermographic measurements of the phantom that was exposed to an electromagnetic field at 60 GHz. The measurement setup for the thermographic measurements is shown in Fig. 10. A 4×4 patch array was used as the radiation source. The phantom was designed to obtain an equivalent temperature rise to the surface of the skin at a steady state [30]. Temperature elevations were measured using a thermographic camera (InfRec H8000, Avio) under the following two exposure scenarios:

- Exposure scenario 1 (Fig. 11 (a)): the phantom aligned at the boresight of the antenna.
- Exposure scenario 2 (Fig. 11 (b)): the phantom tilted 30° from the boresight of the antenna as a TM-like exposure.

The distance between the antenna and phantom surface was fixed at 70 mm. The separation distance was determined to adequately measure the surface temperature using a thermographic camera. Surface temperature elevations were derived for an exposure duration of 30 min. Measurements were repeated six times, and the mean and standard deviations were calculated. The ambient temperature was maintained at 24°C , while the relative humidity was in the range of 50–60%. The PD incident on the phantom was evaluated using a

Fig. 10. Experimental setup for thermal measurements.

Fig. 11. Exposure scenarios for (a) normal incidence and (b) 30° inclined incidence.

measurement system with a WR-15 open-ended waveguide probe (NSI2000, Nearfield Inc.) via the reconstruction technique of incident PD [31].

The measured temperature rises normalized with 1W input power were $9.5 \pm 0.8^\circ\text{C}$ and $7.9 \pm 0.3^\circ\text{C}$ for the exposure scenarios 1 and 2, respectively. The obtained $psPD$ and HF s are summarized in Table IV for each definition of the incident PD and averaging area. $psPD_n$ was smaller for oblique incidence cases than for normal incidence cases, but not for $psPD_{tot}$, as expected. For the normal incidence case, the measured HF_n and HF_{tot} for the 4 cm^2 averaging area were identical. For a 30° TM-like oblique incidence, HF_{tot} is 15.4% lower than that of HF_n . Similar trends were observed from the computational results for the 4×4 patch array shown in Figs. 5(c) and (d), where the difference between the computed HF_n and HF_{tot} is less than 2% for normal incidence, and HF_{tot} is approximately 12.7% lower than HF_n for the 30° oblique incidence case. In addition, the 4-cm^2 averaged results summarized in Table IV demonstrate that HF_n and HF_{tot} for scenario 2 are 7.14% and 21.4% lower than those for scenario 1. The computed HF_n and HF_{tot} for the 4×4 patch array for the 30° oblique incidence were 12.3% and 22.5% lower than those for normal incidence, respectively, agreeing well with experimental results.

TABLE IV
THERMOGRAPHIC MEASUREMENT RESULTS

Exposure scenario	Scenario 1		Scenario 2	
Averaging area [cm^2]	1	4	1	4
$psPD_n$ [W/m^2]	0.90	0.70	0.79	0.62
$psPD_{tot}$ [W/m^2]	0.90	0.70	0.90	0.72
HF_n [$^\circ\text{C}/(\text{W/m}^2)$]	0.011	0.014	0.010	0.013
HF_{tot} [$^\circ\text{C}/(\text{W/m}^2)$]	0.011	0.014	0.0088	0.011

V. CONCLUSION

This paper reports on the effect of the angle of incidence on sPD and the resultant temperature rise using both computational and thermographic measurement approaches.

Two definitions of $psPD$, $psPD_n$ and $psPD_{tot}$, were examined. Based on the intercomparison, good agreement was observed across the research groups. The effects of antenna type, skin model, and antenna-body distance were also discussed. The results demonstrated that both $psPD_n$ and $psPD_{tot}$ were comparable if the assessments were conducted for small or moderate incidence angles. The results also revealed that HF_n is less dependent on the incidence angle than HF_{tot} , which tends to decrease for larger incident angles. For exposure to TM-like polarized waves at Brewster's angle, sPD_n may be less conservative than sPD_{tot} . However, this tendency was primarily observed when the skin model was located distantly from the antenna. For large incidence angles ($> \sim 60^\circ$), the distance between the antenna and illuminated area of the body surface becomes considerably larger than the normal antenna-body distance. Therefore, a high antenna output power is required to generate the corresponding free-space PD, suggesting that the normal incidence scenario is crucial for considering the peak skin temperature rise.

ACKNOWLEDGMENT

The authors would like to thank Prof. Kenneth R. Foster (University of Pennsylvania) and Dr. Jafar Keshvari (Aalto University) for their valuable comments on this work.

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