ABSTRACT
International guidelines/standards for human exposure to electromagnetic fields have recently been revised to update the dosimetric reference limits (DRLs or basic restrictions) and exposure reference levels (ERLs), specifically for frequencies above 6 GHz. At such frequencies, the ERL is defined in terms of incident power density (IPD) and used as a practical quantity to assess compliance with DRLs (absorbed or epithelial power density) and therefore appropriately limits temperature elevation at the body surface. In the exposure standards, IPD is spatially averaged over an area of 4 cm\(^2\) below 30 GHz and 1 cm\(^2\) above 30 GHz, however the definition of IPD is given in a theoretical manner. With the progress in the development of product safety compliance assessment standards, one concern has been how to define the IPD considering practical measurement procedures. Two definitions or averaging methods were considered: using IPD vectors normal to the averaging surface and using magnitude (norm) of IPD vectors. As the exposure guidelines are intended to prevent excessive tissue heating, statistical analysis was therefore undertaken to investigate which IPD metric better correlates with the temperature increase. To this end, a large data set for several exposure scenarios was collected by different research institutions. The analysis of the obtained results is presented and shows that both definitions have high correlation with temperature rise, with slightly better correlation (0.9 vs. 0.8) for the definition using the magnitude of IPD vectors.

INDEX TERMS
5G exposure, heating factor, human safety standard, power density, statistical analysis.

I. INTRODUCTION
With the advent of fifth-generation (5G) mobile devices, assessment of electromagnetic (EM) field exposure at frequencies above 6 GHz is receiving much consideration [1]. At these frequencies, often referred as millimeter-waves (mm-Waves), the established adverse effect on biological tissues is of thermal nature, related to a temperature increase of the superficial tissues, mainly skin and eye [2]–[5].

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International exposure guidelines/standards for human protection from high-frequency electromagnetic fields have been recently revised by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) [6] and the Institute of Electrical and Electronics Engineers (IEEE), with the Technical Committee (TC) 95 [7].

The use of the absorbed/epithelial power density (A/E-PD) as the basic restriction (BR) [6] or dosimetric reference limit (DRL) [7] for the frequencies above 6 GHz is one of the main changes in the guidelines/standards. Furthermore, the incident power density (IPD) in free space is
defined as the reference level (RL) [6] or exposure reference level (ERL) [7]. It should be noted that at mm-Waves, IPD is a more practical and straightforward measurand than the A/E-PD.

Based on the exposure guidelines/standards, the IPD should be averaged over a squared area of 4 cm² for frequencies from 6 to 300 GHz. However, for frequencies higher than 30 GHz, additional criteria of IPD averaged over 1 cm² are given with a relaxation of RL/ERL by a factor of 2 for local beam-like exposures [6], [7]. Since no technical specifications have been provided on how to determine these spatial averaging, some product compliance assessment standards have been established by the International Electrotechnical Commission (IEC) TC106 and IEEE ICES TC34 committees. These dual-logo standards, recently published, provide experimental and numerical procedures to assess exposure to IPD from 6 GHz to 300 GHz [8], [9].

Beside the averaging technique, one of the goals in the development of these assessment standards has been the definition of a robust IPD metric considering practical aspects of laboratory measurement procedures. Two definitions have been proposed so far:

- the first definition, where only normal components of the Poynting vector crossing the surface are used (sPDₜ);
- the second definition, where all total components (i.e., magnitude) of the Poynting vector are considered (sPDₜₒₜₑ tàₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜₒₜₑ tₜ_o
been analyzed, first for dipole data, then for directional antennas data:

- \((psPD_{avg,1}, p\Delta T)\);
- \((psPD_{tot,1}, p\Delta T)\);
- \((psPD_{avg,4}, p\Delta T)\);
- \((psPD_{tot,4}, p\Delta T)\).

To evaluate possible influence of near-field exposure conditions, a distinction has been made by excluding the data coming from the simulations with distance \(d = 2 \text{ mm}\) (i.e., \(d \geq 2 \text{ mm}\)) and the data from all other simulation scenarios, i.e. \(d \geq 2 \text{ mm}\). The scatter plots were aimed at visually establishing the type of correlation (linear or not) and its strength (i.e., strong, weak or no correlation).

**B. STANDARD DEVIATIONS OF HF**

After generating the scatter plots for all data series, the HF data have been analyzed grouping the results by institution/group. To this end, the average value (\(\mu_{HF}\)) and standard deviation (\(\sigma_{HF}\)) for each group have been computed for each of the four metrics, namely \(HF_{avg,1}, HF_{tot,1}, HF_{avg,4}, HF_{tot,4}\). The same computations were also performed considering the data from all groups together. The standard deviation of each HF sample was of particular interest, since a smaller value of \(\sigma_{HF}\) would suggest stronger correlation with \(\Delta T\). Finally, for each PD metric, the histograms of the HF data (computed for all the data sets) have been plotted to examine their distribution around the average value \(\mu_{HF}\).

**C. PEARSON CORRELATION COEFFICIENTS**

The analysis of the Pearson correlation coefficients has been performed to identify the PD metric that best correlates with the temperature increase \(\Delta T\). Specifically, the following Pearson correlation coefficients were evaluated:

- \(r_{n1}\): Pearson coefficient of the pair \((psPD_{avg,1}, p\Delta T)\);
- \(r_{tot1}\): Pearson coefficient of the pair \((psPD_{tot,1}, p\Delta T)\);
- \(r_{n4}\): Pearson coefficient of the pair \((psPD_{avg,4}, p\Delta T)\);
- \(r_{tot4}\): Pearson coefficient of the pair \((psPD_{tot,4}, p\Delta T)\).

Equation (2) was employed for the computation of the correlation coefficients [29]:

\[
r_{jk} = \frac{\text{Cov}(psPD_{avg,k}, p\Delta T)}{\sigma(psPD_{avg,k}) \sigma(p\Delta T)}, \quad j = \{n, tot\}, \quad k = \{1, 4\}
\]

where \(\text{Cov}(psPD_{avg,k}, p\Delta T)\) is the covariance of \(psPD_{avg,k}\) and \(p\Delta T\), while \(\sigma(psPD_{avg,k})\) and \(\sigma(p\Delta T)\) are the standard deviations of \(psPD_{avg,k}\) and \(p\Delta T\), respectively. Each set of four different \(r_{jk}\) was computed considering the distinction between data obtained without including the separation distance \(d = 2 \text{ mm}\) and all other data, namely:

- \(r_{n1}, r_{tot1}, r_{n4}, r_{tot4}\) for dipole and \(d \geq 5 \text{ mm}\);
- \(r_{n1}, r_{tot1}, r_{n4}, r_{tot4}\) for all dipole data.

Each of the four analyses above has been performed on data groups distinguished by the working frequency of the sources. Specifically, correlation coefficients have been computed first for all the available frequencies \((f = 10, 30, 60, 90 \text{ GHz})\), then for the \(f = 10, 30 \text{ GHz}\) set and finally for the \(f = 60, 90 \text{ GHz}\) set, still distinguishing between dipole and directional antennas data. A clear picture of the analysed data groups is given in Tables 3 and 4 in Sec.IV.C.

**D. STATISTICAL SIGNIFICANCE TEST**

Finally, a statistical significance test was carried out to quantify the difference between the correlation coefficients and analyze values of \(r_{jk}\), \(j = \{n, tot\}, k = \{1, 4\}\) in a consistent and objective manner [30]. Such a procedure is also helpful to check whether the noise in the analyzed data had significant effect on the computed values of \(r_{jk}\). In particular, it could be determined if the probability that the difference between \(r_{ap}\) and \(r_{bq}\), \(a \neq b\) is merely due to chance (i.e., noise in the data) with a predefined significance level \(\alpha\) (e.g., \(\alpha = 5\%\) if a confidence level of 95\% is chosen). A simplified scheme of the statistical hypotheses for the testing procedure hereby adopted is described as follows:

1. Define the null and alternative hypotheses. In this analysis, the null hypothesis is defined as \(H_0: \rho_{ap} = \rho_{bq}\), \(a \neq b\) or \(p \neq q\), where \(\rho_{ap}\) and \(\rho_{bq}\) are the true correlation coefficients of the pairs of data samples \((spPD_{avg,p}, \Delta T)\) and \((spPD_{avg,q}, \Delta T)\), while \(\rho_{ap}\) and \(\rho_{bq}\) are their estimators. The alternative hypothesis is defined as \(H_1: \rho_{ap} > \rho_{bq}\), \(a, b, p, q\) such that \(\rho_{ap} > \rho_{bq}\).

2. Employ an appropriate significance test, together with a relevant test statistic. Since the compared correlations have one variable in common (i.e., \(\Delta T\)), the adopted test statistics for dependent correlations are those provided by the \(cocor\) package [30].

3. Choose the significance level \(\alpha\). In this analysis, a value of \(\alpha = 5\%\) has been adopted.

4. Compute the values of \(z\)-scores or \(t\)-scores (i.e., the test statistics) associated to the difference \(r_{ap} - r_{bq}\) based on the observed data.

5. Reject the null hypothesis \(H_0\) if in favour of the alternative hypothesis \(H_1\) if the observed value \(r_{ap} - r_{bq}\) is in the critical region; “fail to reject” (retain) \(H_0\) otherwise.

The last two steps of the testing process are automatically performed by the tool provided in the \(cocor\) package [30]. Results in terms of \(z\)-scores or \(t\)-scores for each of the nine different applied tests are reported in Sec.IV.D.

The procedure above was applied to compare the performance of the normal and total component definitions in terms of correlation with \(\Delta T\), distinguishing the compared coefficients by the averaging area.
IV. STATISTICAL RESULTS

A. SCATTER PLOTS

The scatter plots for the dipole and directional antennas are reported in Figs. 1-4 and 5-8, respectively.

It should be noted as regression lines given by the equation $y_i = s_i x$, with $i = \{5, 2\}$ referring to data with $d \geq 5$ mm or
TABLE 1. HF relative standard deviations [%] sorted by PD metrics. Highlighted in bold are the smallest values for each research group.

|        | $\sigma$ (HF, avg. 1) | $\sigma$ (HF, avg. 4) | $\sigma$ (HF, avg. 1) | $\sigma$ (HF, avg. 4) |
|--------|-----------------------|-----------------------|-----------------------|-----------------------|
| NICT   | 61.67                 | 71.00                 | 60.68                 | 63.79                 |
| NI Tech| 46.72                 | 90.05                 | 92.88                 | 92.88                 |
| SCAU   | 44.06                 | 84.97                 | 83.67                 | 83.67                 |
| 3DS    | 44.53                 | 81.96                 | 53.75                 | 53.75                 |
| IT’IS  | 35.19                 | 73.88                 | 46.35                 | 46.35                 |
| UniSplit | 62.44              | 96.14                 | 69.84                 | 69.84                 |
| All data | 57.02              | 90.09                 | 76.95                 | 76.95                 |

TABLE 2. Ratio of 95th to 5th percentile for the four HF definitions. Highlighted in bold are the smallest values for each metric.

|        | HF, avg. 1 | HF, avg. 4 | HF, avg. 1 | HF, avg. 4 |
|--------|------------|------------|------------|------------|
| Ratio  | 5.72       | 11.22      | 5.18       | 7.77       |

$d \geq 2$ mm, have been included in these plots. They provide insight into the collected data spread amongst the several institutions and simulation case studies, noting sporadic high values of HFs for some of the directional antennas, with particular reference to a pair of values with $p\Delta T$ between 2 and 2.5 °C (see Figs. 5-8). These values correspond to patch array antennas with a beam shift in azimuth or elevation, which have already been reported to exhibit a large spread of HFs [24]–[26]. A quantification of possible effects of these data on the Pearson correlation coefficients is given in Sec. IV.C (see Tables 3-6).

B. RELATIVE STANDARD DEVIATIONS OF HF

The relative standard deviations of the HF obtained for the several PD definitions and metrics from the several research groups are summarized in Table 1. It can be observed from this Table that the $psPD_{tot}$ definition always gives the HF distributions with the least relative standard deviations, except for the case of data provided by NI Tech group, where for the $psPD_n$ definition it is slightly smaller.

The histograms of the HF distributions are shown in Figs. 9-12. The average value of each distribution is demarked with a red dotted vertical line. The occurrence distributions show a noticeable positive skewness in all four cases. Thus, the ratio of the 95th to the 5th percentiles of the HF distributions has been performed to quantify the skewness and the tail length [27]. The computed ratios for each of the four HF definitions are reported in Table 2. Considering that the $psPD_{eq}$ values are in general higher than the $psPD_n$ while the $p\Delta T$ are the same, it can be expected that the associated HF distributions show less dispersed values towards the high end and, thus, a shorter tail. In fact, Table 2 shows that percentile ratios associated with HF$_{tot}$ definitions (bolded highlighted) are smaller than those associated with HF$_n$. 
Finally, the plots of the $HF$ rearranged as a function of electric distance, i.e. the distance $d$ over the wavelength $\lambda$, distinguished by the PD definitions ($HF_n$ vs. $HF_{tot}$), are reported in Figs. 13 and 14 for the 1 cm$^2$ and 4 cm$^2$ averaging areas, respectively. The graphical evaluation of the plots shows that the average value of $HF_n$ is consistently greater than the one of $HF_{tot}$, but this difference diminishes with electrical distance because the tangential components of the Poynting vector tend to vanish in the far-field. Instead, a greater dispersion is observed at distances $d \leq 0.6 \lambda$ (see Figs. 13(a) and 14(a)) due to the near-field zone characteristics.

C. PEARSON CORRELATION COEFFICIENTS

Tables 3 and 4 show the computed values of Pearson correlation coefficients for the dipole source and directional antennas, respectively. In the first case, the PD metric with highest $r_{jk}$ is the one related to the definition of $sPD_{tot1}$, while in the second case, coefficients related to $sPD_{tot1}$ are always higher, with the exception of the 10, 30 GHz data group, where the highest coefficients are $r_{tot1}$ and $r_{tot4}$, respectively. This may be due to the increased capability to focus the beam for the directional antennas.

In addition, when grouping data by separation distance, all the highest $r_{jk}$ values are obtained for $d \geq 5$ mm, except for $r_{tot4}$ in the case of directional antennas at the highest frequencies, where including all distances in the analyses seems to yield higher correlation. In general, the increased correlation, obtained excluding the smallest distance, may be due to the reduced level of tangential components of the Poynting vector in the near-field compared to the reactive components. Finally, when grouping data by the frequency range, it can be observed, as expected, that both PD definitions with 1 cm$^2$ averaging area correlate better than the respective definitions with 4 cm$^2$ for the 60, 90 GHz data set, while this is not always true for the 10, 30 GHz data set.

D. STATISTICAL SIGNIFICANCE TEST

Tables 6 and 7 show the results of the $z$- and $t$-scores analyses considering the data related to 1 cm$^2$ and 4 cm$^2$ averaging areas, respectively. The input values provided to the cocor package in order to perform the significance test are reported in Table 5. In particular, it shows the correlation coefficients compared in pairs, i.e., $r_{n1}$, $r_{tot1}$ and $r_{n4}$, $r_{tot4}$, and the associated coefficients $r_{n1,tot1}$ and $r_{n4,tot4}$, obtained computing the correlation of $sPD_{tot1}$ with $sPD_{tot}$ and $sPD_{n4}$ with $sPD_{tot}$, respectively. A one-tailed test for the hypothesis that $r_n < r_{tot}$ has been performed.

The $z$- and $t$-scores reported in Tables 6 and 7 show that the results have strong statistical significance, with scores well below the critical values related to 95% confidence level. This result confirms that the correlation of the total component
with the peak temperature rise is (statistically) significantly higher than that of the normal component. In fact, all the employed tests led to the rejection of the null-hypothesis $r_n = r_{tot}$. The only exception to this trend comes from the comparison between $r_{n1}$ and $r_{tot1}$ for the directional antennas data, where the two correlations could not be distinguished at the 95% confidence level (see Table 5).

### V. DISCUSSIONS

#### A. EXPLANATION OF THE OBTAINED RESULTS

The results of Table 3 show that, for the simple dipole source, the definition with $sPD_{n1}$ presents highest values of correlation coefficients with temperature rise compared to the definition $sPD_{tot}$, both when grouping the data by separation distance and frequency. The small difference between the values of correlation coefficients corresponding to the two definitions indicates that both resulting quantities correlate strongly with temperature rise (correlation coefficients $>0.7$).

One possible explanation for this is that the scenarios considered in this study are mainly for the normal incidence of the field on the body, thus the differences are relatively small. However, this slightly better correlation with the total components may be attributed to the near-field exposure conditions, where some of the components are obliquely

### TABLE 3. $psPD \times \Delta T$ correlation coefficients related to the dipole source. Highlighted in bold are the highest values for each data set.

| Dipole     | $d$ | $r_{n1}$ | $r_{tot}$ | $r_{n4}$ | $r_{tot4}$ |
|------------|-----|----------|-----------|----------|------------|
| All $f$    | all | 0.862    | **0.895** | 0.776    | 0.868      |
|            | $\geq$ 5 mm | 0.910    | **0.913** | 0.853    | 0.878      |
| 10, 30 GHz | all | 0.831    | **0.874** | 0.754    | 0.856      |
|            | $\geq$ 5 mm | 0.921    | **0.922** | 0.858    | 0.883      |
| 60, 90 GHz | all | 0.897    | **0.920** | 0.812    | 0.892      |
|            | $\geq$ 5 mm | 0.946    | **0.948** | 0.916    | 0.937      |

### TABLE 4. $psPD \times \Delta T$ correlation coefficients relate to the directional antennas. Highlighted in bold are the highest values for each data set.

| Direct. Anten. | $d$ | $r_{n1}$ | $r_{tot}$ | $r_{n4}$ | $r_{tot4}$ |
|----------------|-----|----------|-----------|----------|------------|
| All $f$        | all | 0.806    | 0.805     | 0.637    | 0.769      |
|                | $\geq$ 5 mm | 0.870    | 0.837     | 0.705    | 0.700      |
| 10, 30 GHz     | all | 0.836    | **0.872** | 0.749    | 0.830      |
|                | $\geq$ 5 mm | 0.894    | 0.923     | 0.906    | **0.927**  |
| 60, 90 GHz     | all | 0.833    | **0.858** | 0.709    | 0.643      |
|                | $\geq$ 5 mm | 0.796    | 0.580     | 0.576    |            |

### TABLE 5. Input values for the cocor analysis. Highlighted in bold are the highest values for each data set.

| Source       | avg. | $r_n$ | $r_{tot}$ | $r_{n,tot}$ |
|--------------|------|-------|-----------|-------------|
| Dipole       | 1 cm$^2$ | 0.862 | **0.895** | 0.9869      |
|              | 4 cm$^2$ | 0.776 | **0.868** | 0.9696      |
| Directional  | 1 cm$^2$ | 0.806 | 0.805     | 0.9331      |
|              | 4 cm$^2$ | 0.637 | **0.769** | 0.8121      |

### TABLE 6. $z$-scores and $t$-scores of the $psPD_{avg.1}$ and $\Delta T$ correlation comparison between data belonging to the dipole source and to the directional antennas. In the Null-Hypothesis column, rej. stands for rejected and ret. stands for retained.

| Source       | avg. | z- or t-test | $z$- or t-score | Null-Hypothesis |
|--------------|------|--------------|-----------------|-----------------|
| Pearson and Filon's | t | 0.305 | 0.0155 | rej. | ret. |
| Hotelling's  | t | -0.056 | 0.0155 | rej. | ret. |
| Williams'    | t | -0.045 | 0.0154 | rej. | ret. |
| Olkin's      | z | -0.366 | 0.0156 | rej. | ret. |
| Dunn and Clark's | z | -0.412 | 0.0154 | rej. | ret. |
| Hendrickson et al. | t | -0.046 | 0.0154 | rej. | ret. |
| Steiger's    | z | -0.458 | 0.0154 | rej. | ret. |
| Meng et al.  | z | -0.458 | 0.0154 | rej. | ret. |
| Hittner et al. | z | -0.456 | 0.0154 | rej. | ret. |

### TABLE 7. $z$-scores and $t$-scores of the $psPD_{avg.4}$ and $\Delta T$ correlation comparison between data belonging to the dipole source and to the directional antennas. In the Null-Hypothesis column, rej. stands for rejected and ret. stands for retained.

| Source       | avg. | z- or t-test | $z$- or t-score | Null-Hypothesis |
|--------------|------|--------------|-----------------|-----------------|
| Pearson and Filon's | t | -0.932 | 0.3638 | rej. | rej. |
| Hotelling's  | t | -1.322 | 0.3617 | rej. | rej. |
| Williams'    | t | -1.388 | 0.3279 | rej. | rej. |
| Olkin's      | z | -0.832 | 0.3529 | rej. | rej. |
| Dunn and Clark's | z | -0.832 | 0.3529 | rej. | rej. |
| Hendrickson et al. | t | -0.932 | 0.3638 | rej. | rej. |
| Steiger's    | z | -0.714 | 0.4800 | rej. | rej. |
| Meng et al.  | z | -0.714 | 0.4800 | rej. | rej. |
| Hittner et al. | z | -0.704 | 0.4566 | rej. | rej. |
incident to the model. Furthermore, excluding the data for the shortest distance of 2 mm, which is considered as near-field exposure (at least below 30 GHz), the correlation is generally improved. In other words, the correlation at 2 mm is very poor highlighting the limitation of IPD as RL/ERL metric at close distances.

Differently from the dipole, exposure to more complex sources yields to a less clear picture. In fact, while the power density and heating values corresponding to the dipole sources are consistent and do not show any particular clustering of values or alarming variability, the data coming from the simulations of directional antennas are obviously characterized by larger variations in the correlation coefficients (see Table 4) and by the presence of some outliers in their distribution. The latter can be found also in the scatter plots (see Figs. 5-8) with some $p\Delta T$ values between 2 and 2.5 °C. Considerations about possible health risks from such high temperature increases and conservative safety margins lie outside the scope of this work.

B. METHOD AND DATA COLLECTION LIMITATIONS

When conducting a statistical analysis, a crucial aspect is the analysis of the available set of data, both in terms of sample size and nature of the collected data. In particular, for the former aspect, it is a good practice to establish whether the size of the analyzed samples is sufficient to guarantee a certain significance of the statistics. In this study, it has been verified that all the chosen samples for both dipole data (115) and directional antennas data (112) were large enough to properly represent their respective statistical population of values. Specifically, an analysis on the tolerance limits conducted through $t$-statistics has shown that, at the 95% confidence level, the errors obtained by estimating the population means through the samples average falls between ~11.8% and ~16.4%.

Regarding the nature of the collected data, a critical aspect may be represented by the fact that they come from different organizations. However, a study of body model and thermal parameter variability impact for frequencies below 30 GHz was performed in [27] showing that the difference in HF’s were globally below 20%. The authors of [27] concluded that, although the slight dependency on the body model, thermal parameters, and antenna models, the deviation of HF’s is insignificant when considering the numerical methods used by different organizations.

VI. CONCLUSION

The observation of correlation coefficients, computed for the different data samples, shows that, in general, the spatial averaged power density metrics based on total components (i.e., magnitude) provide a slightly higher correlation than those based on the normal components. However, the difference is marginal (0.9 vs. 0.8) and the close values of correlation coefficients show that both definitions correlate with temperature elevation.

Moreover, the analysis of the heating factor distributions for different normal exposure configurations shows smaller relative standard deviation values when applying an $sPD_{tot}$ definition. Consequently, this definition is expected to yield a slightly better estimate of the induced temperature increase than $sPD_{tot}$. The observed difference is however not large and can mainly be attributed to near-field conditions.

Finally, the analysis of the statistical significance test confirmed that the PD definition using all total components correlates with temperature rise slightly better than the PD definition using the normal components (see Table 5). On the basis of the obtained results, we conclude that the $sPD_{tot}$ is the definition that should be recommended as IPD metric in International exposure guidelines/standards for human protection.

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