

Toward Next-Generation Exposure Metrics for the Communication Systems

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Abstract:

The rapid evolution of 6G networks and the increasing adoption of Terahertz (THz) communication systems require the accurate and reliable exposure metrics to ensure the safe and efficient deployment, such systems operating in 0.1-10 THz frequency range. The next generation exposure metrics essential to investigate the impact of THz radiation on human being and the environment. This paper explores the induced electric field, absorbed power density and temperature rise dosimetric instead of SAR metrics at THz frequencies for human skin tissue. The results shows that the absorbed power density and temperature raise in human skin are found within standards limits given by international agencies like International commission on Non- Ionizing Radiation Protection (ICNIRP) and institute of Electrical and Electronics Engineers (IEEE). Further more we examine the current state of research on biological materials and to understand the potential biological effects of THz radiation on humans.

Keywords: EMR. SAR metrics, power density dosimetric, Terahertz frequency, etc.

1. INTRODUCTION:

The rapid development of wireless communication technologies, including fourth-, fifth-, and sixth-generation (6G) systems, has been fueled by the increasing need for ultra-high data rates, low latency, and smooth connectivity. To meet these performance standards, communication systems beyond the fifth generation are planned to expand their operational spectrum into the terahertz (THz) frequency range, which is usually characterized as being between 0.1 and 10 THz. This spectral region has an extremely wide bandwidth, which allows data to be sent at speeds of terabits per second. This makes THz frequencies especially useful for short-range mobile communications, wearable electronics, and body-centric wireless networks (Akyildiz et al., 2014; Chowdhury et al., 2020). It will be impossible for people to escape THz electromagnetic radiation when THz technologies are expected to be used in mobile and personal wireless devices. This kind of exposure is likely to happen mostly in the near-field region, where mobile devices are used close to the head on a regular basis. THz radiation, on the other hand, has very shallow penetration depths. This is different from regular radiofrequency (RF) radiation at sub-6 GHz frequencies, where electromagnetic waves can go several centimeters into biological tissues. This phenomenon is mainly due to the significant absorption of water molecules, which quickly weakens the electromagnetic field in the outermost layers of the skin (Foster et al., 2017). As a result, the scalp and the superficial layers of the head are the primary sites of energy deposition during exposure to terahertz (THz) radiation emitted by handheld devices. The specific absorption rate (SAR) is the most widely used metric for quantifying human exposure to electromagnetic radiation. The SAR is still a good measure at

lower frequencies, but it doesn't work as well at frequencies above around 6 GHz, which includes the millimeter-wave and THz bands. At these higher frequencies, energy absorption is limited to tissue layers that are considerably thinner than the average mass utilized in standard SAR calculations, making volumetric SAR estimations physically and biologically less significant (IEEE, 2019). Acknowledging these constraints, worldwide exposure standards now advocate for absorbed or epithelial power density as the optimal dosimetric metric for localized exposure evaluation in the millimeter-wave and THz frequency ranges (ICNIRP, 2020). Power density-based dosimetry provides a more accurate physical characterization of the interaction between electromagnetic energy and biological tissues at THz frequencies. This method directly measures the power that hits and is absorbed by the outer layers of skin, taking into account losses due to reflection at the air-skin interface and quick loss of power within the skin layers. At THz frequencies, electromagnetic interaction mechanisms are primarily governed by surface absorption and near-surface heating, rather than volumetric energy deposition (Alekseev and Ziskin, 2018). Numerical simulations and experimental investigations have demonstrated that localized temperature rises can occur in skin tissues subjected to THz exposure, even at moderate incident power densities, highlighting the necessity for precise power density estimation (Sasaki et al., 2017). In addition to thermal effects, numerous experimental investigations have explored potential non-thermal biological impacts of THz radiation, including documented alterations in gene expression, membrane permeability, and cellular metabolic processes. There is a lot of disagreement among scientists about whether or not these effects exist and how important they are. However, most scientists agree that any biological response is strongly affected by the power density of the incident and absorbed light, the length of time of exposure, and the dielectric properties of the tissues that were exposed (Smye et al., 2001; Wilmink and Grundt, 2011). This emphasizes the need for a reliable, frequency-dependent dosimetric framework for evaluating exposure to terahertz (THz) radiation. As mobile devices are commonly used in close proximity to the head, the scalp becomes a key region for assessing THz electromagnetic exposure. In this context, the present study undertakes a power density-based dosimetric assessment of human scalp exposure to terahertz radiation emitted by mobile devices. The analysis considers electromagnetic field distributions, the dielectric properties of scalp tissues, and applicable international safety guidelines. Such studies are crucial for clarifying exposure characteristics, evaluating potential health risks, and ensuring that future THz-enabled mobile communication devices operate safely within established regulatory limits.

2. Methodology:

2.1 Interaction of EMR with human health:

The interaction of RF/MW radiation with living system, including human being is a complex function of many parameters. Biological responses are due to the EMF inside the biological body. The amount of radiation reflected, transmitted and absorbed for a given exposure field, is determined with the help of electrical properties of living systems. The exposure field is characterized by the frequency, intensity, polarization and near-field of a radiator. The interaction of biological material with an electromagnetic source depends on the frequency of the source (Moulder and Foster, 1995). It can be considered on a macroscopic or microscopic (molecular, cellular) level. On the molecular level, two basic mechanisms govern the interactions, viz., space charge polarization at lower RF and field-induced rotations of polar molecules at higher RF and microwave frequencies (Health Aspects, Part I and II, 1977, 1978). The space charge polarization is due to travelling charge carriers, i.e., ions and the applied field affects the

whole movement of the ions. Polar molecules, i.e., molecules having an uneven spatial distribution of charges, such as water and proteins, experience a torque when placed in an electric field. Both of these mechanisms are of a relaxation character. In moderate fields, only a relatively small number of charges or molecules are actually affected by the field. The thermal motion of molecules and charges hinders the movements, and the kinetic energy undergoes a conversion into the thermal energy. In these interactions, the electromagnetic energy is converted into kinetic energy of molecules, and subsequently converted into thermal energy which produce heating or raise the body temperature (McIntosh et al., 2005).]

When EMR from transmission towers falls on the human body, then it penetrates into it and affecting the biological tissues of body. The electric field is propagated from the tower in all directions and thus the value of electric field depends upon the distance r from the tower and its transmission power P is given by Polk (1996)

$$\frac{P}{4\pi r^2} = \frac{E_0^2 \epsilon_0 c}{2}$$

Where c is speed of light or EMR and ϵ_0 is the permittivity of free space.

$$E_0 = \frac{P}{(2p^2 \epsilon_0 c)^{\frac{1}{2}}}$$

$$E_0 = \frac{7.746 \sqrt{P}}{r}$$

Thus, the electric field around the transmission tower is inversely proportional to the distance from the towers. The electric field at depth z inside human body due to incident electric field E_0 on the surface of body is given by Polk (1996)

$$E_z = E_0 \exp\{-z/d\}$$

Where d is the skin depth (The distance at which the field is reduced to $1/e$ of its original value at the boundary). It depends upon the frequency of radiation for biological body is given by

$$d = \frac{1}{q\omega}$$

$$q = \left[\frac{\mu\epsilon\{(1+p^2)^{\frac{1}{2}} - 1\}}{2} \right]^{\frac{1}{2}}$$

$$p = \frac{\sigma}{\omega\epsilon}, \quad \omega$$

ω = radian frequency of radiations,

ϵ = Permittivity of tissue material

μ = Permeability of tissue material

σ = Conductivity of tissue material.

The above mathematical formulation can be used to evaluate the electric field inside the human body tissues at different depths.

2.2 Power Density Formulation and Its Relation to Temperature Rise

1. Instantaneous power density (pointing vector)

The instantaneous electromagnetic power flow per unit area is described by the **Poynting vector**, given by

$$S = E \times H$$

E is the instantaneous electric field (V/m), and H is the instantaneous magnetic field (A/m).

2. Time –Averaged power density

For time-harmonic electromagnetic fields, the time-averaged power density is expressed as the real part of the complex Poynting vector, which represents the average electromagnetic power incident on the skin surface.

$$S = |E|^2 / \eta$$

E denotes the root mean square (RMS) electric field strength at the scalp, expressed in volts per meter (V/m), and η represents the intrinsic impedance of free space, with a value of 377 Ω .

3. Relationship between power density and surface temperature rise

The surface temperature elevation resulting from absorbed electromagnetic power can be approximated by

$$\Delta T \cong \frac{S_{abs}}{h}$$
$$S_{abs} = S_{inc}(1 - R)$$

In this relation, ΔT denotes the surface temperature rise ($^{\circ}\text{C}$), S_{abs} represents the absorbed surface power density (W/m^2), and h is the heat transfer coefficient between the skin and the surrounding air, typically in the range of 10–20 $\text{W}/\text{m}^2\cdot\text{K}$. The reflection coefficient R accounts for power reflected at the air–skin interface and are approximately 40% of the incident power density. This expression indicates that surface temperature elevation at terahertz frequencies is governed primarily by the magnitude of absorbed power density and the effectiveness of heat dissipation from the skin surface.

3. Observations:

3.1. Mobile phone Base Stations

Mobile base stations operated at THz frequency, the electric field distribution at the human skin surface is characterized by relatively high magnitudes and pronounced spatial non-uniformity. Both numerical simulations and experimental investigations have reported approximate values of the root mean square (RMS) electric field at different superficial tissue depths. As a result, the electric field becomes increasingly concentrated near the skin surface, leading to enhanced surface exposure and diminished field levels at greater depths (Gandhi et al., 2012; Christ et al., 2010)

3.2. 5G Sub-6 GHz Base Station (Far-Field Exposure)

Exposure arising from fifth-generation (5G) sub-6 GHz base stations occurs predominantly in the far-field region, where the electromagnetic field distribution is comparatively uniform and the field strengths are significantly lower than those associated with near-field exposure from handheld devices. In typical urban deployments operating around 3.5 GHz, the electric field levels experienced by the general public at head or scalp height remain relatively low. For outdoor exposure scenarios at distances of approximately 1- 5 m from a base station, reported RMS electric field strengths at the scalp generally fall within the range of 1–10 V/m. The large margin between measured or estimated environmental field strengths and the applicable regulatory limits indicates that exposure from sub-6 GHz 5G base stations does not pose a significant thermal risk under normal operating conditions (ICNIRP, 2020; Joseph et al.,

2010). As a result, electromagnetic energy absorption is confined to the skin layers, with negligible field penetration into deeper tissues. These exposure characteristics are consistent with previously reported experimental and computational studies (Sasaki et al., 2017; Alekseev and Ziskin, 2018).

3.3 Power density at Terahertz Frequencies

Since the biological interaction at THz frequencies is dominated by surface absorption, volumetric metrics such as specific absorption rate (SAR) are no longer representative. In contrast, power density provides a direct measure of how much electromagnetic energy reaches the skin and enables accurate estimation of the resulting surface temperature rise.

Table 1. Terahertz (0.1 THz)–Induced Electric Field and Power density distribution in the Human Skin

Distance from the mobile Base Station (Meter)	Incident Electric Field (V/m)	Induced Electric field (V/m)			Incident Power density (W/m ²) x10 ⁻³		
		1 mm	2mm	3mm	1mm	2 mm	3 mm
1	17.32	4.56	1.20	0.32	55.0	3.8	0.27
2	8.66	2.28	0.60	0.16	14.0	0.95	0.067
3	5.77	1.52	0.40	0.11	6.12	0.42	0.032
4	4.33	1.14	0.30	0.08	3.44	0.24	0.016
5	3.46	0.91	0.24	0.06	2.19	0.15	0.009

Table 2. Power density–Based Dosimetric Parameters and associated Temperature Rise in the Human Skin

Distance from the mobile base station (Meter)	Absorbed Power density (W/m ² x10 ⁻³)			Temperature rise (Degree Centigrade)X 10 ⁻³		
	1 mm	2mm	3mm	1mm	2mm	3mm
1	55.0	3.8	0.27	2.2	0.152	0.01000
2	14.0	0.95	0.067	0.56	0.038	0.00266
3	6.12	0.42	0.032	0.24	0.016	0.00128
4	3.44	0.24	0.016	0.14	0.009	0.00060
5	2.19	0.15	0.009	0.09	0.006	0.00033

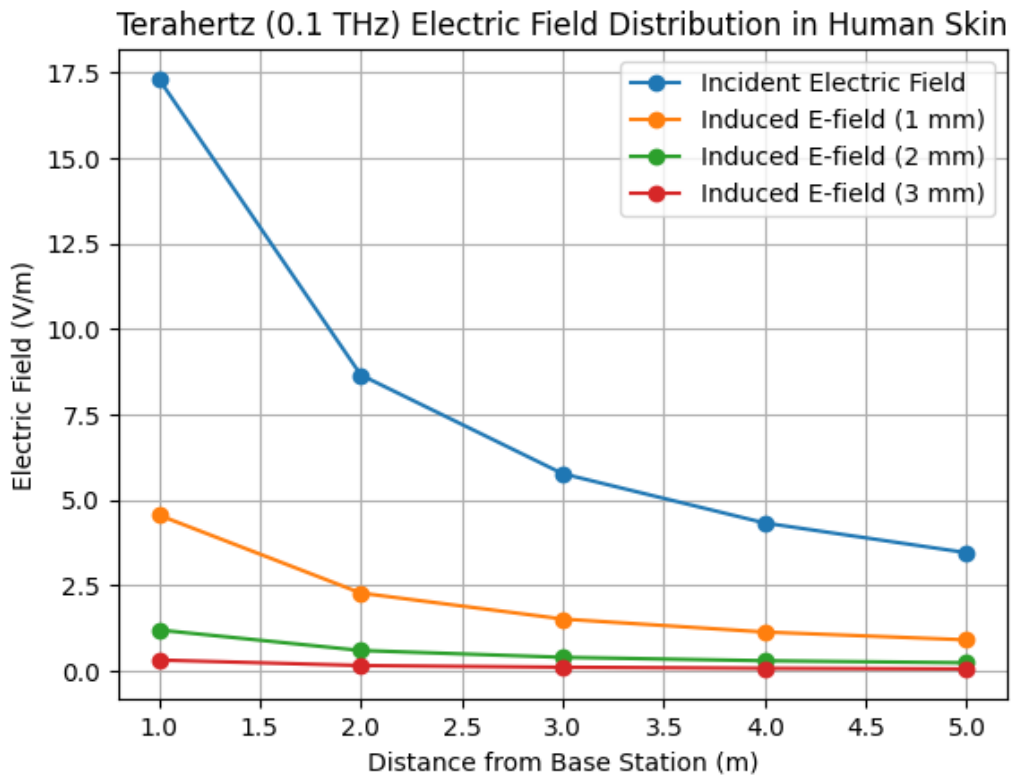


Figure 1. Variation of induced electric field with distance from mobile base stations

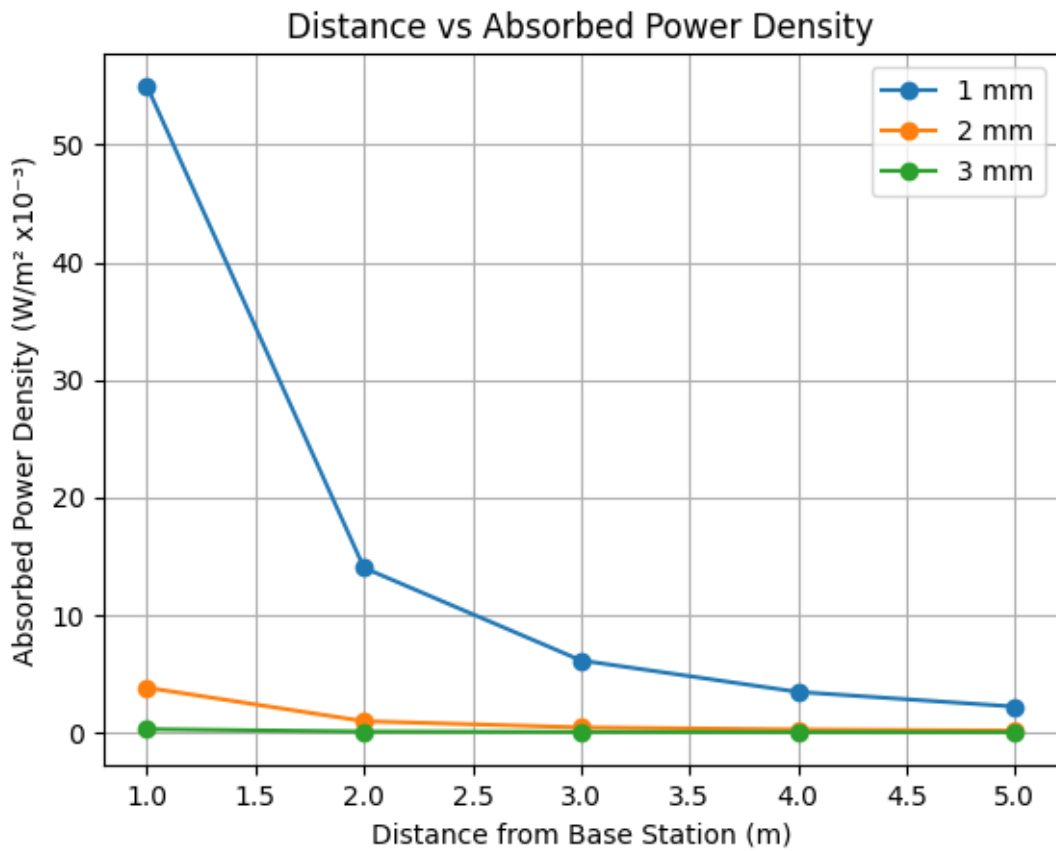


Figure 2. Variation of absorbed power density with distance from mobile base stations

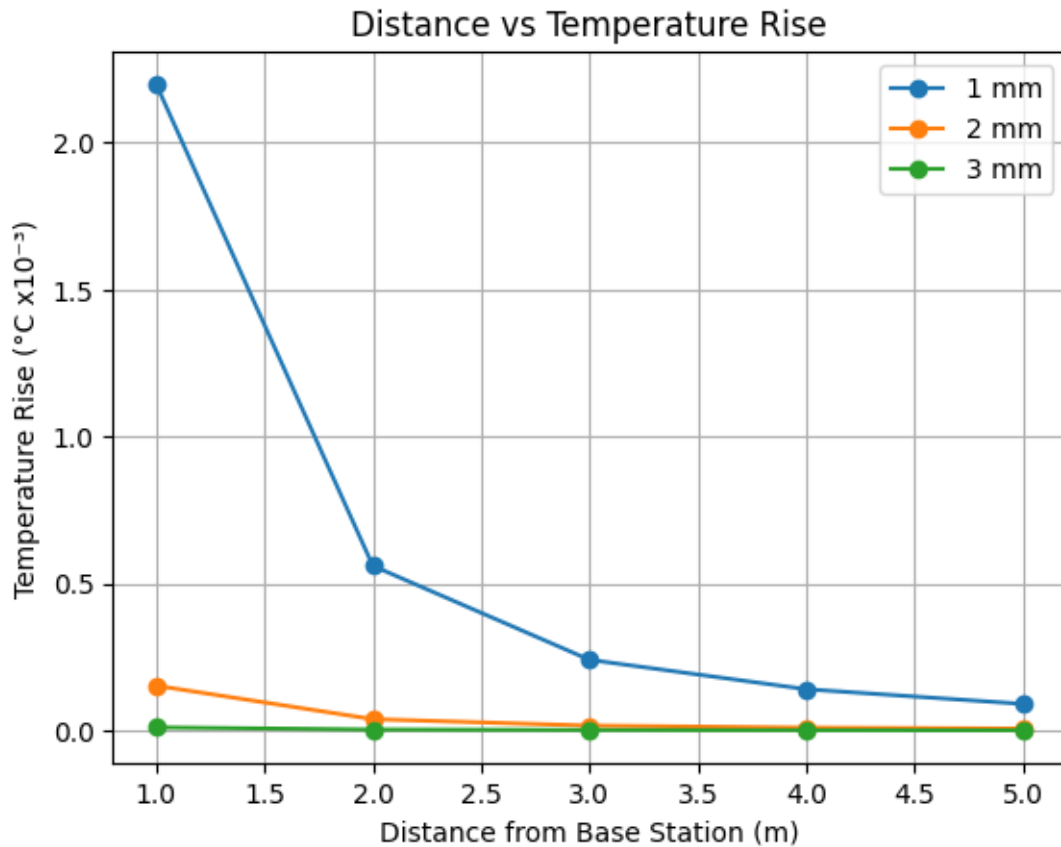


Figure 3. Variation of temperature rise with distance from mobile base stations

Results and discussion:

The graphical presentation in figures 1, 2 & 3 shows a rapid decay in induced electric field, absorbed power density and temperature rise with increasing distance from the mobile base station. The absorption is maximum at superficial depths (1 mm) and decreases significantly at deeper skin tissue layers, indicating strong surface confinement of electromagnetic energy. The corresponding temperature rise follows a similar trend, demonstrating a direct proportionality between absorbed power and thermal effects. The extremely low temperature elevations, even at minimum distances, suggest negligible thermal hazards. These findings confirm that high-frequency electromagnetic radiation primarily induces superficial heating and supports the use of power density as a more relevant dosimetric metric than SAR in THz exposure assessment.

At terahertz frequencies, human exposure assessment is appropriately carried out using surface power density and the corresponding temperature elevation in the skin, rather than volumetric energy absorption metrics. The estimated temperature rise in the human skin remains well below 1 °C, which lies within internationally accepted safety limits. According to international safety standards, the permissible power density limits are 10 W/m² for the general public and 50 W/m² for occupational exposure. These limits are designed to ensure that the localized temperature increase in exposed tissues remains minimal and biologically safe. Temperature elevations exceeding approximately 2–3 °C may lead to thermal stress and discomfort, while temperatures above 5 °C can pose a risk of irreversible tissue damage depending on exposure duration. The temperature rise predicted in the present assessment remains far below these thresholds, confirming compliance with established thermal safety criteria.

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