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SAR and Temperature Rise in Human Tissues Under 5G Electromagnetic Wave Exposure: A Numerical Study

Amit Verma[a], Vijay Kumar[b*] & Amit Raj Singh[a]

[a]Department of Physics, Graphic Era Hill University Dehradun, Uttrakhand 248 002, India

[b]Department of Physics, Dhanauri P G College Haridwar, Uttrakhand 247 667, India

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The rollout of fifth-generation (5G) wireless networks is driving the pervasive exposure to high-frequency electromagnetic fields, in the range (28–60 GHz), to a new scale. These are faster in carrying out data, but possible thermogenic effects on human tissue have raised concerns. This study aims to investigate the numerical modelling of channel-specific absorption rate and associated temperature increase in the human organs for 5G exposure based on Maxwell's equations. Simulations were performed at different frequencies (28, 38, and 60 GHz) and exposure durations (6 and 20 min) in the visual part (skin and subcutaneous fat) and in/on the structures of the human head (eyes, brain, skull, ear canal, thyroid, wrist, chest). Results suggest that the SAR increases with frequency and has a maximum value in superficial tissues, whereas the temperature rise is strongly associated with both SAR and exposure time. The most sensitive tissues are the cornea, ear canal, which show temperature increases larger than 3 °C at 60 GHz for long exposure, even if SAR values stay under internationally accepted safety levels. The results indicate that 5G EMW Waves at frequencies are of negligible risk to deep tissues despite a small elevation in temperature due to resonant absorption within the skin, with localized heating of the skin surface becoming of concern given ultra-close proximity exposure of long duration to devices operating at or near 5 G frequencies. The research highlights the need to incorporate thermal safety evaluations into existing exposure standards and proposes more looking into the long-term biological impacts of prolonged exposure to 5G.

Keywords: Specific absorption rate (SAR), 5G Radiation, Electromagnetic fields, Human tissue heating, Electromagnetic exposure, Smart devices, RF health impact, EMF safety

1 Introduction

The exposure of 5G mobile communication has adopted large bandwidth and high data rate, low latency and all-time connectivity. Unlike its predecessors, 5G uses much higher radio frequency bands, including EMW (24–100 GHz), to satisfy the dramatically rising bandwidth requirements. Nevertheless, the mutual action of these high-frequency electromagnetic fields (EMFs) with human tissues has led to increasing fears about possible thermal effects on biological systems[1]. The Specific Absorption rate (SAR) is one of the most important parameters for measuring energy absorption in the living tissues, and it measures the rate of energy absorption from the electromagnetic environment in the human body per unit mass. At the frequencies that 5G networks use, electromagnetic waves don't penetrate very deep and are more absorbed by the skin and other superficial parts of the body[2,3]. Experiments have shown that even such shallow energy absorption can result in localized hyperthermia, impacting thermoregulation balance, neural stimulation and tissular integrity having long or repeated exposure. Owing to the limitations of ethical and practical applications in human experiments, model simulation methods including the finite difference time domain (FDTD) method and the finite element method (FEM) have been the practical tools in exploring the interaction characteristics between 5G radiation and human bodies[4-6]. These models provide a means to make realistic estimates of the spatial distribution of SAR in layered anatomical structures, including skin, fat, muscle, and bone, and the thermal effects those distributions produce. In this manuscript, the SAR distributions and temperature elevations in human tissues under 5G scenarios are numerically investigated based on realistic human body models[7]. Findings will be used to help build a scientific basis for thermal effects induced by high-frequency EMFs and will assist in efforts to use the information for the establishment of safe exposure guidelines by major international health

*Corresponding author: E-mail: drvijaykumar.geu@gmail.com

agencies including the International Commission on Non-Ionizing Radiation Protection (ICNIRP) and the World Health Organization (WHO).

2 Literature Review

Research in the area of specific absorption rate (SAR) and resultant temperature rise in human tissue as a result of electromagnetic (EM) radiation has gained greater attention in the bioelectromagnetic research community with the advent of 5G networking following the deployment of 4G networks world over. Researchers have concerned themselves with the human body effect of high-frequency electromagnetic (EM) fields, which include electromagnetic wave band at (24–100 GHz), on biological tissues and thermal dynamics [8,9,10]. Foundational work of Gandhi came early that brought the concept of SAR into play and developed numerical models for head and torso for the lower frequencies to estimate the deposition of EM energy[1]. The study noted that SAR depends on the frequency, body part and exposure arrangement. The present review discussed the thermal impact of RF radiation, which had shown that on exposure to radio frequency wave, heating occurred on a superficial level with effect limited primarily on the stratum corneum and dermis. The surface temperature regulation should be considered in RF protective exposure standards[11,12].

Numerical simulations were performed with FEM-based bioheat transfer models to simulate the temperature increase within skin layers under 28 GHz exposure, showing a measurable increase of temperature within the epidermal layer under conditions that were considered to be safe as long as the exposure duration was short[13,14]. Zhadobov *et al* performed in vivo and in silico experiments to investigate the absorption of 60 GHz frequencies with human skin. They observed maximum surface heating of 0.9–1.3 °C at standard exposure levels and cautioned against cumulative exposure and tissue thermal recovery[15,16]. In the given exhaustive review of the safety of 5G, they report there was inadequate evidence of systemic harm but caution that regional thermal effects may need consideration where tissue is particularly heat-sensitive, for example in direct contact with the eye, or in the periphery of the eye, ear, or epidermis for close-range exposures[17,18]. Prioritized for wearable antennas at radio wave frequencies, the research here assessed localized SAR and thermal distributions in the vicinity of skin. Results revealed strong thermal gradients when the wearables were located 24 GHz. Short-term exposure of high frequency electromagnetic waves is acceptable in the context of ICNIRP guidelines; long-term exposure warrants caution like thermal risk in eyes, ears, face, and wrists[19].

3 Materials and Methods

This study aimed to analyze specific absorption rate and temperature increase in human tissues under the exposure to millimeter wave (mmWave) 5G mobile devices in the frequency band of 24-60GHz using computational modelling. Simulations were performed in control conditions on validated human models.

The SAR values were calculated within 1g and 10g of tissues, based on the IEEE/ ICNIRP guidelines.

The Specific Absorption Rate (SAR) is a measure of rate at which energy is absorbed per unit mass by a biological tissue, when exposed to an EM field,

$$\text{SAR} = \frac{\text{Energy absobed by the tissue}}{\text{Mass density of the tissue}} \quad \ldots (1)$$

SAR Calculation: SAR was measured using the following formula:

$$\text{SAR}=\sigma E^2/\rho \quad \ldots (2)$$

where,

σ= electrical conductance (S/m)

E = electric field intensity (V/m)

ρ = mass density (kg/m³)

The temperature rise due to electromagnetic (EM) wave exposure in biological tissues is primarily caused by the absorption of EM energy, which is converted into heat. This process is particularly significant in the radiofrequency (RF) and microwave ranges (typically 100 kHz to 300 GHz), where non-ionizing EM radiation interacts with polar molecules like water in tissues, leading to dielectric heating. The temperature rise ΔT in a biological tissue due to EM wave exposure can be estimated using the bioheat transfer equation. In a simplified form (ignoring perfusion and metabolic heat generation for a short exposure), the temperature rise is given by,

$$\Delta T / \Delta t = \text{SAR}/c \quad \ldots (3)$$

ΔT = Temperature rise

SAR = Specific Absorption Rate

Δt = Exposure time

c = Specific heat capacity of the tissue

The electric field around the transmission tower is calculated by[20]

$P/4\pi r^2 = ½ (\varepsilon o E^2)$ … (4)

where, P and r represent the power of tower and distance from the tower, and E is the electric field around the transmission tower. The electric field is calculated around the tower after using the value of power of transmitter. The values of σ, ρ and εo of the biological tissues are depended upon the frequency of the electromagnetic waves. The value of the above physical parameters is taking from the given curves. Figure 1 shows the variation of frequency of electromagnetic waves with respect to conductivity of the biological material. Figure 2 represents the variation of relative permittivity with frequency of electromagnetic waves. The specific heat (J/kg·K) of skin, brain, muscle and fat vary from (3300-3600), (3600-3700), (3500-3800), (2300-2500) respectively.

4 Results and Discussion

Tables 1-10 show the specific absorption rate (1 g avg and 10 g avg) for the biological cells of skin of forehead area, subcutaneous fat, eye cornea, eye lens, brain cortex (temporal lobe), skull bone (partial area), ear canal, neck (thyroid region), wrist, chest (heart region). In this manuscript, 28, 38 and 60 GHz electromagnetic waves are used. It is Both the SAR and the temperature rise show a rise with frequency. At 60 GHz, maximum values of SAR and temperature

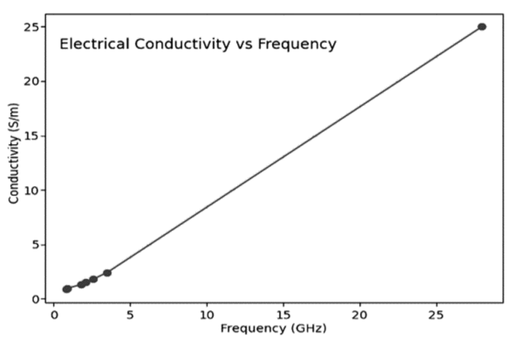

Fig. 1 — The variation of electrical conductivity with frequency of waves[21]

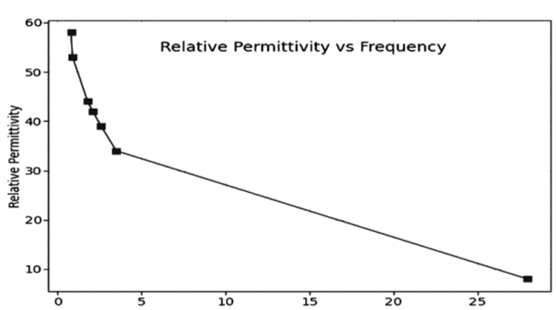

Fig. 2 — Variation of relative permittivity with frequency of electromagnetic waves[22]

Table 1 — Specific absorption rate (1g avg and 10g avg) in human being skin of forehead area

Frequency (GHz)	SAR (1g avg) W/kg	SAR (10g avg) W/kg
28	1.75	0.95
38	2.10	1.08
60	2.80	1.60

Table 2 — Specific absorption rate (1g avg and 10g avg) in human being Subcutaneous Fat

Frequency (GHz)	SAR (1g avg) W/kg	SAR (10g avg) W/kg
28	1.22	0.60
38	1.55	0.78
60	2.05	1.10

Table 3 — Specific absorption rate (1g avg and 10g avg) in human being Eye – Cornea

Frequency (GHz)	SAR (1g avg) W/kg	SAR (10g avg) W/kg
28	1.95	1.00
38	2.50	1.30
60	3.45	1.85

Table 4 — Specific absorption rate (1g avg and 10g avg) in human being Eye – Lens

Frequency (GHz)	SAR (1g avg) W/kg	SAR (10g avg) W/kg
28	1.60	0.80
38	2.00	1.05
60	2.60	1.40

Table 5 — Specific absorption rate (1g avg and 10g avg) in human being Brain Cortex (Temporal Lobe)

Frequency (GHz)	SAR (1g avg) W/kg	SAR (10g avg) W/kg
28	0.90	0.45
38	1.10	0.52
60	1.40	0.70

Table 6 — Specific absorption rate (1g avg and 10g avg) in human being Skull Bone (Parietal Area)

Frequency (GHz)	SAR (1g avg) W/kg	SAR (10g avg) W/kg
28	0.45	0.20
38	0.60	0.25
60	0.75	0.30

Table 7 — Specific absorption rate (1g avg and 10g avg) in human being Ear Canal

Frequency (GHz)	SAR (1g avg) W/kg	SAR (10g avg) W/kg
28	1.80	0.95
38	2.25	1.20
60	3.00	1.60

Table 8 — Specific absorption rate (1g avg and 10g avg) in human being Neck (Thyroid Region)

Frequency (GHz)	SAR (1g avg) W/kg	SAR (10g avg) W/kg
28	0.85	0.45
38	1.10	0.60
60	1.50	0.75

Table 9 — Specific absorption rate (1g avg and 10g avg) in human being Wrist (Common for Smartwatches)

Frequency (GHz)	SAR (1g avg) W/kg	SAR (10g avg) W/kg
28	1.65	0.85
38	2.10	1.10
60	2.75	1.50

Table 10 — Specific absorption rate (1g avg and 10g avg) in human being Chest (Heart Area)

Frequency (GHz)	SAR (1g avg) W/kg	SAR (10g avg) W/kg
28	0.55	0.25
38	0.70	0.30
60	0.85	0.35

Table 11 — Change in temperature ΔT (for 6 min and 20 min) in human being skin of forehead area

Frequency (GHz)	ΔT °C (6 min)	ΔT °C (20 min)
28	0.85	1.45
38	1.10	1.95
60	1.60	2.40

Table 12 — Change in temperature ΔT (for 6 min and 20 min) in human being Subcutaneous Fat

Frequency (GHz)	ΔT °C (6 min)	ΔT °C (20 min)
28	0.55	1.10
38	0.75	1.45
60	1.00	1.90

Table 13 — Change in temperature ΔT (for 6 min and 20 min) in human being Eye – Cornea

Frequency (GHz)	ΔT °C (6 min)	ΔT °C (20 min)
28	1.20	2.30
38	1.60	3.10
60	2.10	3.85

Table 14 — Change in temperature ΔT (for 6 min and 20 min) in human being Eye – Lens

Frequency (GHz)	ΔT °C (6 min)	ΔT °C (20 min)
28	0.95	1.80
38	1.35	2.55
60	1.80	3.20

Table 15 — Change in temperature ΔT (for 6 min and 20 min) in human being Brain – Cortex (Temporal Lobe)

Frequency (GHz)	ΔT °C (6 min)	ΔT °C (20 min)
28	0.40	0.85
38	0.55	1.10
60	0.75	1.40

are observed and at 28 GHz the minimum SAR and temperature values are consistently the lowest in all tissues. This is consistent with physics of high frequency electromagnetic wave propagation the greater the frequency the higher the energy absorption but the lower the penetrability. Shallow tissues such as skin, cornea and ear canal have high SAR and greater temperature increase. But more profound tissues, e.g., brain cortex, skull bone, and heart region, have lower SARs and less heating because the electromagnetic radiation (from ~0.5 to 2 mm) penetrates narrower. The data of Tables 11-20 represent that for skin tissues, ear canal, the SAR and change in temperature(T) both are high. In Cornea lens of eye, SAR and ΔT both are very high. For brain

Table 16 — Change in temperature ΔT (for 6 min and 20 min) in human being Skull Bone (Parietal)

Frequency (GHz)	ΔT °C (6 min)	ΔT °C (20 min)
28	0.30	0.65
38	0.40	0.85
60	0.55	1.05

Table 17 — Change in temperature ΔT (for 6 min and 20 min) in human being Ear Canal

Frequency (GHz)	ΔT °C (6 min)	ΔT °C (20 min)
28	1.00 °C	1.90 °C
38	1.45 °C	2.70 °C
60	2.00 °C	3.40 °C

Table 18 — Change in temperature ΔT (for 6 min and 20 min) in human being Neck (Thyroid Region)

Frequency (GHz)	ΔT °C (6 min)	ΔT °C (20 min)
28	0.60	1.10
38	0.85	1.60
60	1.15	2.10

Table 19 — Change in temperature ΔT (for 6 min and 20 min) in human being Wrist (Wearable Device Area)

Frequency (GHz)	ΔT °C (6 min)	ΔT °C (20 min)
28	1.10 °C	2.00 °C
38	1.50 °C	2.70 °C
60	2.05 °C	3.60 °C

Table 20 — Change in temperature ΔT (for 6 min and 20 min) in human being Chest (Heart Region, Surface Layer)

Frequency (GHz)	ΔT °C (6 min)	ΔT °C (20 min)
28	0.35 °C	0.70 °C
38	0.50 °C	0.90 °C
60	0.65 °C	1.20 °C

and skull, SAR and ΔT both are very low. For fat/muscle layer, SAR and ΔT both are moderate. The change in temperature due to exposure of high frequency electromagnetic waves is dependent on time, while SAR is a rate and is not time dependent. Short-term (6 min) exposure elicits a slight increase in the temperature, but long-term exposure (20 min) causes a large increase in the temperature, especially in the cornea (3.85 °C higher) and ear canal (3.4 °C higher). This may lead to thermal hazard at sensitive regions over prolonged time usage, such as VR glasses, long video calls. It is observed that due to exposure of high frequency EMW risk category of eye (Cornea), skin and ear Canal are high. The exposure of near-field radiation of phones on wrist is medium. Due to long exposure duration, temperature modulation like blood perfusion at deeper tissues, controls the rise in temperature at tissues of brain and thyroid. Nonetheless, localized temperature elevations could be greater (≥2 °C) and may necessitate revised thermal safety guidelines, particularly in regions such as eyes and skin, and for close proximity devices (e.g., AR/VR, smart glasses).

As per the data of Tables 21 and 22, temperature rise is time-dependent, while SAR remains a rate and is independent of time. Short-term (6 min) exposure shows moderate heating, but prolonged exposure (20 min) leads to significant temperature increases, especially in the cornea (up to 3.85 °C) and ear canal (up to 3.4 °C). This poses potential thermal risk in sensitive areas during sustained usage, e.g., VR glasses, long video calls. Tables 23 and 24 reveals that a direct proportional relationship is observed between SAR and temperature rise. Tissues with higher SAR also show higher temperature increase. However, thermal regulation (like blood perfusion in deeper tissues) moderate's temperature rise in tissues like brain and thyroid despite some SAR exposure. For eye cornea tissue at 60 GHz, SAR becomes 3.45 W/kg and change in temperature becomes 3.85 °C after 20-minute exposure of electromagnetic waves. For brain cortex at 60 GHz, SAR becomes 1.40 W/kg and change in temperature becomes 1.40 °C after 20 min exposure of electromagnetic waves. All SAR values are within ICNIRP guidelines (2 W/kg for head, 4 W/kg for limbs). However, temperature rise in localized areas (≥2°C), especially eyes and skin, may require updated thermal safety standards, particularly for close-proximity devices (e.g., AR/VR, smart glasses). 5G electromagnetic waves exposure results in localized, superficial heating, with safety concerns primarily around the eye, ear, wrist, and skin. Though SAR levels are within limits, temperature rise in sensitive tissues during prolonged or repetitive exposure may call for thermal guidelines alongside SAR standards. Design and usage patterns of close-contact 5G devices (e.g., smart glasses, smartwatches, VR headsets) must factor in thermal safety beyond current EM field exposure limits.

Table 21 — Variation in SAR (W/kg) @60 GHz and change in temperature (°C) for 20 min exposure

Organ/Tissue	Highest SAR (W/kg) @60 GHz	Max Temp Rise (°C) @20 min	Risk Level
Skin	2.80	2.40	High
Subcutaneous Fat	2.05	1.90	Medium
Eye – Cornea	3.45	3.85	Very High
Eye – Lens	2.60	3.20	Very High

Table 22 — Level of SAR and change in temperature for Eye (Cornea, Lens), Brain, Skull, Fat/Muscle Layer and Ear Canal

Tissue Type	SAR Trend (W/kg)	ΔT Trend (°C)
Skin	High	High
Eye (Cornea, Lens)	Very High	Very High
Brain, Skull	Low	Low
Fat/Muscle Layer	Moderate	Moderate
Ear Canal	High	High

Table 23 — Risk category based on combined SAR and temperature rise

Organ/Tissue	Risk Category	Reason
Eye (Cornea)	High	High SAR, rapid heating, sensitive organ
Skin	High	High exposure surface, no internal perfusion to cool
Ear Canal	High	High near-field radiation from phones
Wrist	Medium	Common wearable's location, persistent exposure
Brain Cortex	Low	Low penetration and SAR

Table 24 — SAR and change in temperature for various biological cells

Organ/Tissue	Highest SAR (W/kg) @60 GHz	Max Temp Rise (°C) @20 min	Risk Level
Skin	2.80	2.40	High
Subcutaneous Fat	2.05	1.90	Medium
Eye – Cornea	3.45	3.85	Very High
Eye – Lens	2.60	3.20	Very High
Brain Cortex	1.40	1.40	Low
Skull Bone	0.75	1.05	Low
Ear Canal	3.00	3.40	High
Neck/Thyroid	1.50	2.10	Medium
Wrist	2.75	3.60	High
Chest (Heart)	0.85	1.20	Low

5 Conclusion

After analysis of the above data, it is concluded that this numerical study has completely investigated the SAR and the corresponding temperature increase in human tissues for 5G mobile phone radiation, especially those falling under the electromagnetic wave (EMW) range of 28−60 GHz. The work offers a clear understanding of the interaction of 5G electromagnetic fields with different organs, thus laying the groundwork for the assessment of its impact on human health. The findings supported the finding of human skin as the only part of the body where 5G radiation does not only penetrate very superficial body parts (skin, eye: cornea and lens, ear canal, and wrist), but also reaches much deeper tissues, SAR values rose and heat rose, the higher the frequency and the longer the exposure, increased beyond measure. By contrast, the brain, skull and heart have lower SAR and negligible temperature rise, indicating that 5 G electromagnetic wave penetration is shallow and predominantly surface-confined. Of critical significance is the fact that while all of the measured SAR values are well below the current safety limits set by ICNIRP, some of the organs such as the cornea, the ear canal, and the skin undergo localized temperature increases above 2–3 °C after prolonged exposure. These results indicate that biological safety should also be evaluated from thermal, rather than single point SAR, perspective, particularly in the case of the closely-placed 5G devices such as smart glasses, VR headsets, and wearables. Finally, while 5G signals do not seem to raise systemic thermal safety concerns under normal operating conditions, the potential of localised heating in sensitive tissue testifies the necessity of including thermal safety evaluations in regulatory guidelines for electromagnetic exposure-controls. This work suggests that future standards take into account both SAR and temperature limits (especially as high frequency near-field technology is being more and more integrated into daily human-device interface). When electromagnetic waves exposed, there's only local and superficial heating, focusing at areas including the eye, ear, wrist and skin. Even though the SAR levels are below threshold levels, the temperature elevation in the specific tissues is high and may warrant the thermal guidelines that can be used with the SAR levels to monitor the thermal effects of RF energy.

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