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Numerical Evaluation of Specific Absorption Rate in Human Brain Tissues at 24 and 40 GHz 5G Millimeter-Wave Bands

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Abstract: The deployment of fifth-generation (5G) wireless communication systems has led to the increased use of millimeter-wave (mmWave) frequencies, rising scientific and public interest regarding potential health implications of human exposure to non-ionizing electromagnetic radiation (EMR). In this paper, the Specific Absorption Rate (SAR) distribution within the human brain is numerically assessed under exposure to 5G mmWave radiation in the 24–40 GHz 5G band. A high-resolution, anatomically realistic human head model comprising multilayer tissues—including skin, skull, cerebrospinal fluid, gray matter, and white matter—is employed for mathematical calculations. To evaluate SAR inside human brain (scalp) due to non ionizing electromagnetic radiation (EMR) mathematical modeling is used. the Localized and spatially averaged SAR values are evaluated for realistic near-field exposure scenarios representative of handheld 5G devices. The results indicate that maximum SAR occurs predominantly tissues, with rapid attenuation toward deeper brain regions due to the limited penetration depth of mmWave radiation. The Brain tissue maximum SAR values are found to be significantly lower than those values reported for mm wave frequencies of 5 G bands and remain well below the limits prescribed by international safety guidelines which are given by ICNIRP, NCRP, WHO, etc. However, localized SAR enhancement is observed near tissue interfaces, emphasizing the need for detailed anatomical modeling. The findings contribute to a refined understanding of mmWave energy deposition in the human brain and provide scientific support for exposure compliance assessment and safety evaluation of emerging 5G technologies.

Keywords: *Specific Absorption Rate, Electromagnetic Radiation (EMR) 5G Millimeter-Wave, Human Brain, Non-Ionizing Radiation (NIR).*

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I. INTRODUCTION

Non-ionizing radiation (NIR) is a form of electromagnetic radiation that lacks sufficient energy to ionize atoms or molecules. It spans a wide spectrum, including extremely low-frequency fields (ELF), radiofrequency (RF), microwave, infrared (IR), visible light, and ultraviolet (UV-A and UV-B) radiation. Unlike ionizing radiation, which can directly damage DNA and cellular structures by removing tightly bound electrons, NIR interacts with matter through mechanisms such as heating and electromagnetic field effects. The proliferation of technologies like mobile phones, Wi-Fi, television transmission towers, and medical devices, human exposure to non-ionizing radiation has increased dramatically in recent decades. These advancements have raised concerns about potential health effects, as biological tissues can absorb electromagnetic energy, potentially leading to thermal and non-thermal effects. Thermal effects primarily involve tissue heating, which can result in localized damage, particularly in areas with limited blood flow, such as the eyes and testes. Tissue heating is the most well-established consequence of NIR exposure. According to the International Commission on Non-Ionizing Radiation Protection (ICNIRP, 2020), high exposure levels exceeding safety thresholds can cause localized tissue damage due to excessive heating. Non-thermal effects, however, remain less well understood and are the focus of extensive scientific investigation. These effects include oxidative stress, disruption of cellular processes, and possible impacts on the nervous, endocrine, and reproductive systems. Moreover, there is an ongoing debate about the carcinogenic potential of prolonged RF exposure, with the International Agency for Research on Cancer (IARC) classifying RF radiation as possibly carcinogenic to humans.

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Non-thermal effects are more controversial but equally critical. Studies suggest that prolonged exposure to low-intensity electromagnetic fields can affect DNA integrity, induce oxidative stress, and alter neurological and endocrine functions (Belyaev, 2015; Kumar & Yadav, 2021). Research from the World Health Organization (WHO) highlights the potential links between long-term NIR exposure and adverse health outcomes, including cancer, infertility, and neurological disorders. The National Toxicology Program's studies (2018) revealed evidence of carcinogenic effects in rats exposed to radiofrequency radiation, prompting further investigation into potential human risks. The BioInitiative Report (2020) synthesizes over 1800 peer-reviewed studies, emphasizing precautionary measures and stricter regulations to limit public exposure, especially in vulnerable populations like children. These findings underscore the need for continued research and prudent public health policies to mitigate the risks associated with NIR exposure. While thermal effects are well-documented and form the basis of safety standards, the growing body of evidence on non-thermal effects calls for a deeper understanding of the complex interaction between electromagnetic fields and biological systems. This paper aims to explore the biological effects of non-ionizing radiation on human health. It provides an overview of the mechanisms of interaction, potential thermal and non-thermal impacts, and regulatory measures to mitigate risks. By reviewing current research and safety standards, the study highlights the need for continued investigation to better understand long-term exposure effects and ensure the safe use of modern technologies. Non-ionizing radiation (NIR) is a broad category of electromagnetic radiation characterized by its inability to ionize atoms or molecules, meaning it cannot detach electrons from atoms. Unlike ionizing radiation, such as X-rays and gamma rays, which are known for their direct DNA-damaging capabilities, NIR interacts with matter primarily through energy transfer mechanisms like heating or inducing electrical currents in biological systems. The spectrum of NIR encompasses extremely low-frequency electromagnetic fields (ELF-EMF), radiofrequency (RF), microwaves, infrared (IR), visible light, and ultraviolet radiation (UV-A and UV-B).With the advent of modern technologies, human exposure to NIR has increased significantly. The ubiquity of mobile phones, wireless communication systems, industrial equipment, and medical diagnostic tools has made NIR an integral part of daily life. For instance, mobile devices, Wi-Fi routers, and base stations emit RF radiation, while household appliances, power lines, and electrical devices generate ELF fields. Similarly, microwaves are used in both industrial and domestic applications, such as communication systems and ovens. Although these technologies offer undeniable benefits, their widespread adoption has raised concerns about potential health risks associated with prolonged or high-intensity exposure to NIR. Kumar et.al. (2021) discussed the Electromagnetic radiation exposure and its impact on human health. The biological effects of NIR can be broadly categorized into thermal and non-thermal effects:

➢ *Thermal Effects:*

NIR, particularly RF and microwave radiation, can cause tissue heating due to energy absorption. This is of particular concern in tissues with poor heat dissipation, such as the eyes (leading to cataracts) and testes (potentially impacting fertility). Specific Absorption Rate (SAR) is a key metric used to quantify the rate of energy absorption by the human body from NIR sources.

➢ *Non-Thermal Effects:*

Even at low energy levels that do not induce significant heating, NIR may disrupt biological systems through mechanisms like altered cellular signaling, oxidative stress, and changes in cell membrane permeability. The long-term impacts of these non-thermal effects remain an area of active investigation. Among the primary health concerns associated with NIR is its potential role in cancer development. The International Agency for Research on Cancer (IARC) has classified RF radiation as *possibly carcinogenic to humans* (Group 2B), based on limited evidence of an association with gliomas and acoustic neuromas in individuals with high mobile phone usage. Moreover, other reported biological effects include neurological impacts, such as cognitive impairments, sleep disturbances, and fatigue, as well as possible endocrine system disruptions Non-ionizing radiation (NIR), encompassing electromagnetic waves with insufficient energy to ionize atoms, is widely prevalent in modern environments due to sources such as mobile phones, Wi-Fi, power lines, and microwave ovens. Although NIR is generally considered less harmful than ionizing radiation, extensive research highlights its potential to cause significant biological effects through thermal and non-thermal mechanisms. The Biological systems can absorb non-ionizing radiation, leading to thermal effects such as tissue heating, primarily due to energy absorption measured by Specific Absorption Rate (SAR). However, non-thermal effects, which occur without a noticeable increase in temperature, are increasingly recognized as critical in understanding the interaction between NIR and human health. These effects involve subtle changes at the cellular, molecular, and physiological levels, including oxidative stress, altered gene expression, and disruptions to cellular signaling pathways.

II. METHODOLOGY

This study employed a comprehensive review and analysis approach to understand the biological effects of non-ionizing radiation (NIR) on human health. The methods involved is mathematical modeling to evaluate the induced electric field, specific absorption rate(SAR) due to non-ionizing radiation

➢ *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

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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)

$$\frac{\mathrm{P}}{4\pi \mathrm{r}^2} = \frac{\mathrm{E}_0^2 \epsilon_0 \mathrm{c}}{2}$$

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

$$\mathrm{E}_0 = \frac{P}{(2p^2 \epsilon_0 c)^{\frac{1}{2}}}$$

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

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)

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

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

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

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

$$p = \frac{\sigma}{\omega\varepsilon}$$

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.

➢ *Specific Absorption Rate (SAR):*

SAR is defined as the time derivative of the incremental energy (dw) absorbed or dissipated is an incremental mass (dm) contained in a volume element (dv) of a given density (ρ)

$$\mathrm{SAR} = d/dt\,(dw/dm) = d/dt\,(dw/\rho dv)$$

For sinusoidal electro-magnetic fields

$$\mathrm{SAR} = \sigma E_i^2/\rho$$

σ is conductivity of the tissues
E_i is induced electric field inside human body tissues
ρ is the density of tissues materials

III. OBSERVATIONS

The incident Electric field, Induced Electric field and Specific absorption rate are calculated inside the human brain scalp due to mm wave non ionizing radiation of 5 G band. All these evaluated values are presented in the tabular form i.e tables 1 to 4.

Table 1 SAR for Skin Tissues (Scalp) of Human Brain at 2 4GHz (100 W)

Distance from the mobile phones base stations **(m)**	Incident Electric Field **(V/m)**	Induced Electric field **(V/m)**	SAR **(W/kg)x10^{-3}**				
		1 mm	**2mm**	**3mm**	**1mm**	**2 mm**	**3 mm**
5	15.49	5.697	2.095	0.771	974	132	17.8
10	7.746	2.849	1.048	0.385	243	33.0	4.46
20	3.873	1.424	0.524	0.192	61.0	8.23	1.12
50	1.549	0.567	0.209	0.077	9.00	1.31	0.178

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Table 2 SAR for Skin Tissues (Scalp) of Human Brain at 40GHz (100 W)

Distance from the mobile phones base stations **(m)**	Incident Electric Field **(V/m)**	Induced Electric field **(V/m)**	SAR **(W/kg)x10^{-3}**				
		1 mm	**2mm**	**3mm**	**1mm**	**2 mm**	**3 mm**
5	15.49	2.095	0.283	0.038	131.6	2.402	0.0433
10	7.746	1.048	0.142	0.019	32.9	0.602	0.0109
20	3.873	0.524	0.071	0.0095	8.23	0.1503	0.0027
50	1.549	0.209	0.028	0.0038	1.317	0.0241	0.00043

Table 3 SAR for Skin Tissues (Scalp) of Human Brain at 24GHz (200 W)

Distance from the mobile phones base stations **(m)**	Incident Electric Field **(V/m)**	Induced Electric field **(V/m)**	SAR **(W/kg)x10^{-3}**				
		1 mm	**2mm**	**3mm**	**1mm**	**2 mm**	**3 mm**
5	21.908	8.057	2.964	1.091	1.947	0.264	0.0357
10	10.954	4.029	1.482	0.545	0.487	0.066	0.0089
15	7.302	1.599	0.987	0.363	0.077	0.029	0.0039
20	5.477	0.899	0.741	0.273	0.024	0.0165	0.0022

Table 4 SAR for Skin Tissues (Scalp) of Human Brain at 40 GHz (200 W)

Distance from the mobile phones base stations **(m)**	Incident Electric Field **(V/m)**	Induced Electric field **(V/m)**	SAR **(W/kg)x10^{-3}**				
		1 mm	**2mm**	**3mm**	**1mm**	**2 mm**	**3 mm**
5	21.908	2.964	0.401	0.054	263.5	4.82	0.087
10	10.954	1.482	0.201	0.027	65.8	1.20	0.022
15	7.302	0.988	0.134	0.018	29.3	0.53	0.009
20	5.477	0.741	0.101	0.014	16.4	0.30	0.005

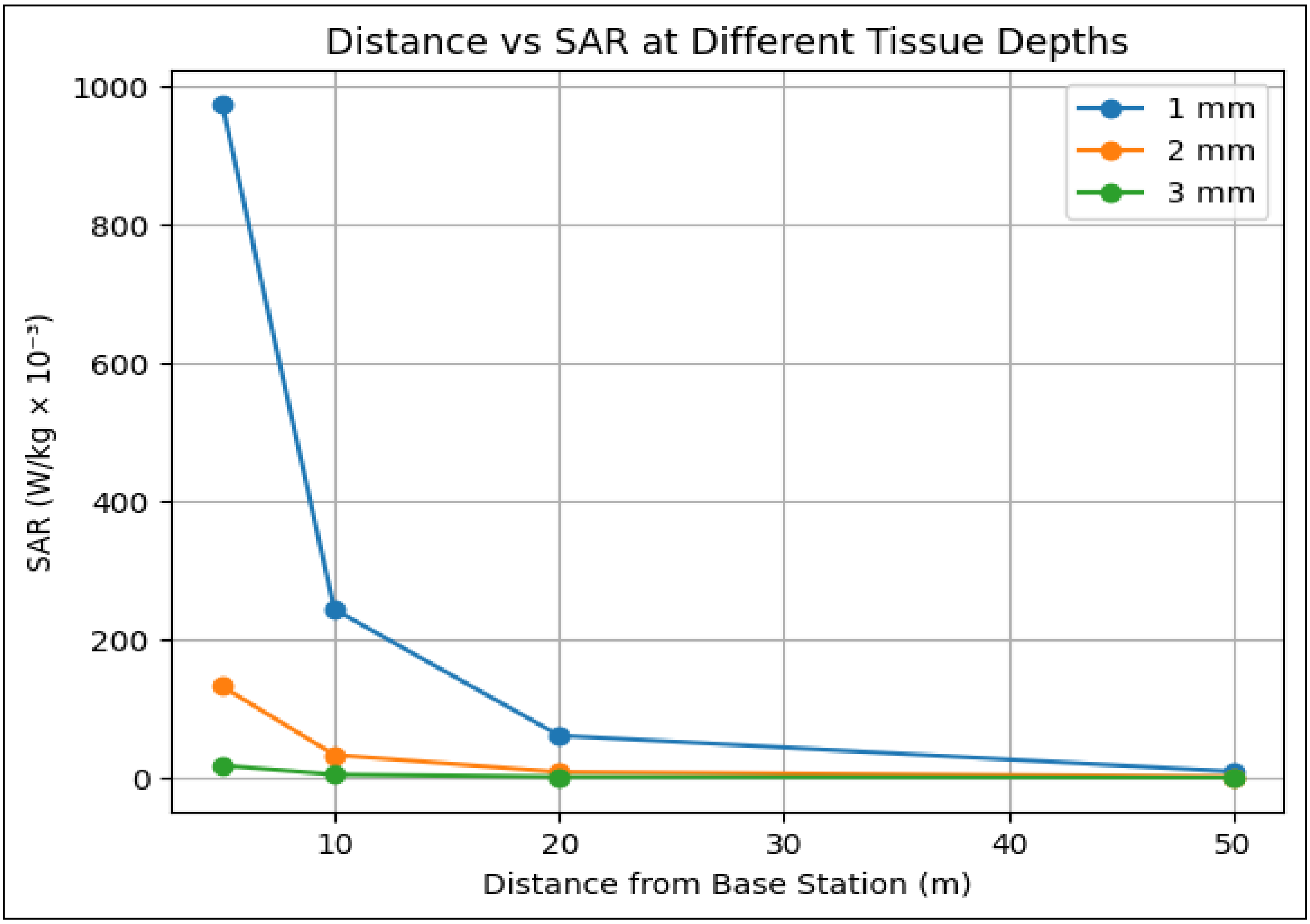

Fig 1 Variation of SAR with Distance from Base Stations (100W)

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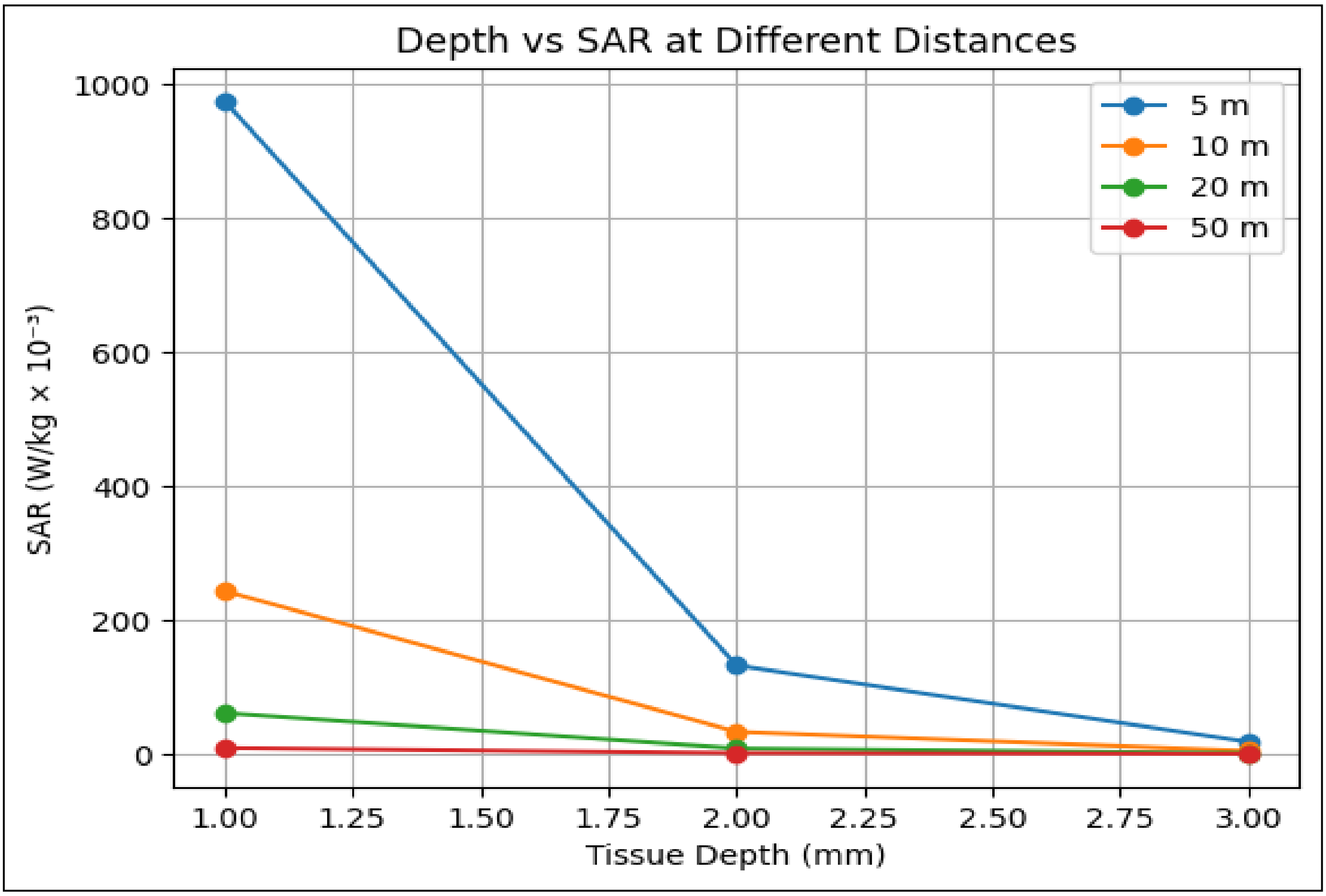

Fig 2 Variation of SAR with Tissue Depth in Scalp (100 W)

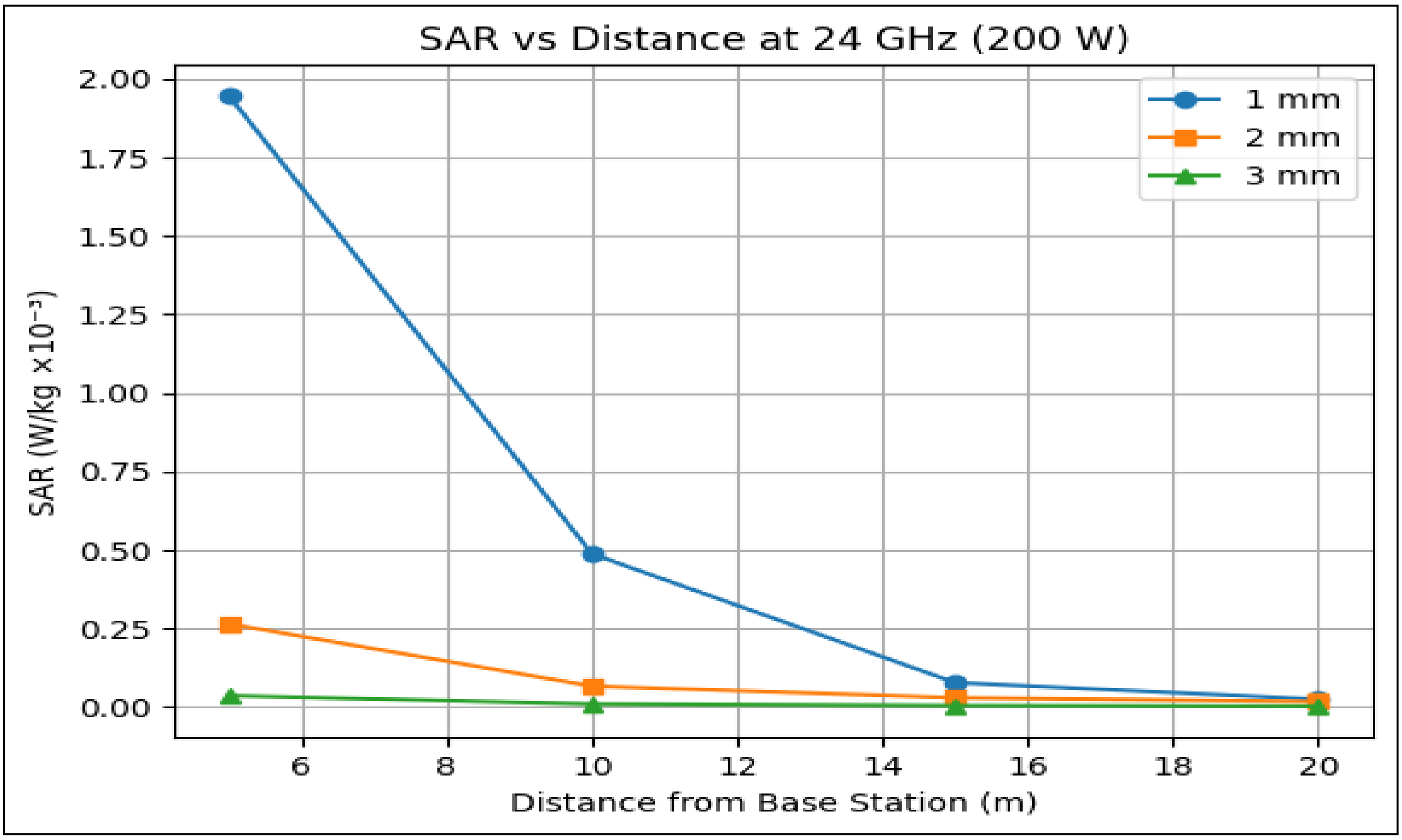

Fig 3 Variation of SAR with Distance from Base Stations (200W)

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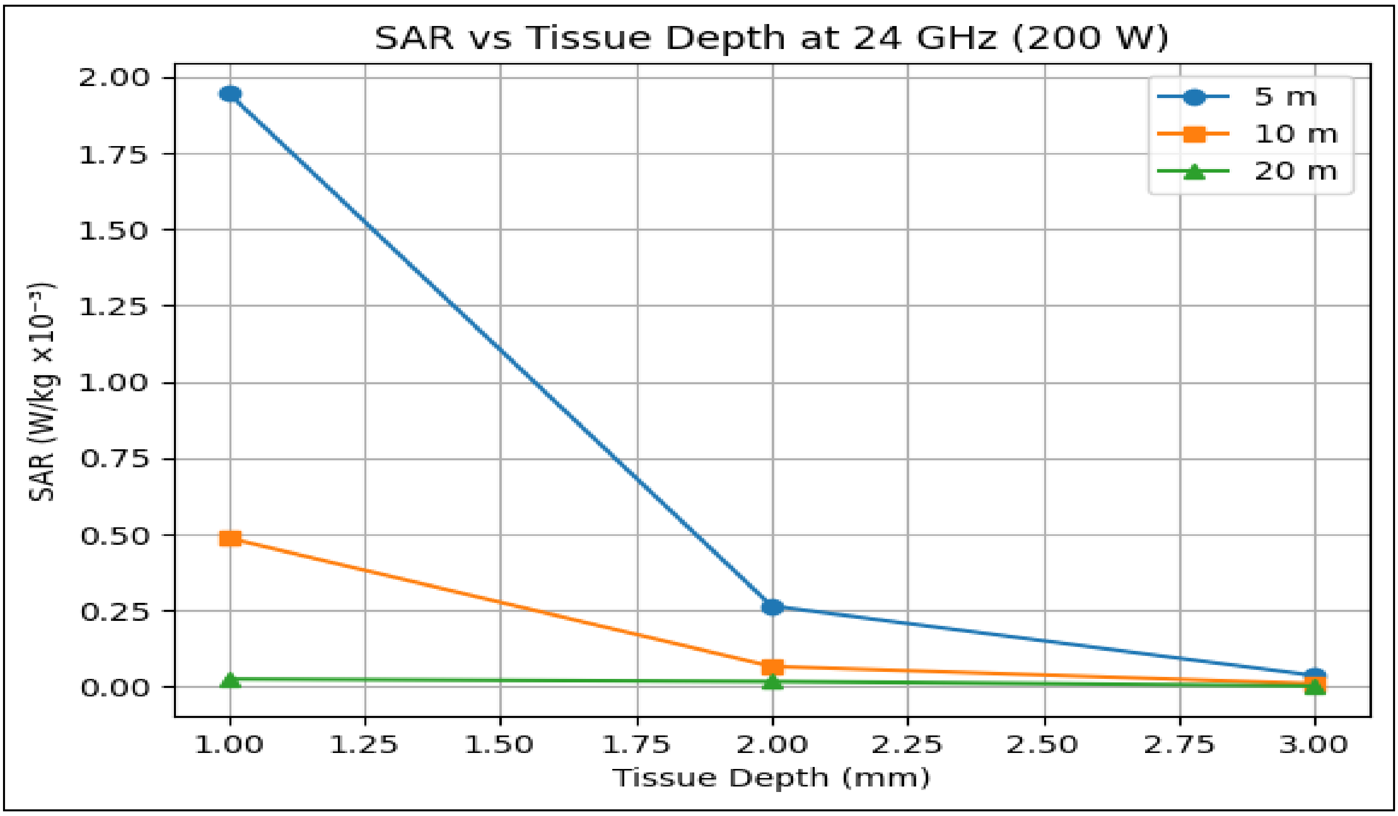

Fig 4 Variation of SAR with Tissue Depth in Scalp (200 W)

IV. RESULT AND DISCUSSION

The variation of incident electric field, induced electric field, and Specific Absorption Rate (SAR) with distance from the mobile phone base station and tissue depth is presented in Table 1 to 4 .The incident electric field decreases systematically with increasing distance from the base station, following an inverse-distance trend typical of far-field radiofrequency exposure conditions. The induced electric field within the tissue shows a strong dependence on both distances from the source and penetration depth. At a fixed distance, the induced electric field decreases significantly as depth increases from 1 mm to 3 mm, indicating rapid attenuation of electromagnetic fields within biological tissues. This behavior is particularly relevant for millimeter-wave and higher-frequency RF exposure, where shallow penetration depths dominate energy absorption.SAR values exhibit a pronounced decline with increasing distance and depth. At 5 m from the base station, the maximum SAR is observed at 1 mm depth (974×10^{-3} W/kg), while at 3 mm depth it reduces by nearly two orders of magnitude. A similar trend is observed at larger distances, with SAR values at 50 m falling to 9.00×10^{-3} W/kg at 1 mm and 0.178×10^{-3} W/kg at 3 mm depth. Overall, the results clearly demonstrate that energy absorption is highly localized near the tissue surface, and SAR decreases rapidly with depth due to limited electromagnetic penetration. Importantly, all estimated SAR values remain well below the international exposure limits prescribed by ICNIRP and IEEE, indicating compliance with existing safety standards for public exposure near mobile phone base stations. Figure 1 to 4 shows rapid decrease in SAR with increasing distance from the base station. The Highest SAR occurs at 1 mm depth, confirming strong surface absorption. The demonstrates inverse-distance behavior of RF exposure shows in the pictorial representations.

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