Assessment of Electromagnetic Field Exposure to Humans at 2.4 GHz Wi-Fi Frequency

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***Abstract*—The purpose of the presented research is to investigate the thermal effects caused by electromagnetic field (EMF) exposure to humans at 2.4 GHz Wi-Fi frequency using numerical simulations. The finite-difference time-domain (FDTD) method-based simulation software FDTDLab was used for the numerical calculations.**

Based on EM and thermal simulations, we estimated the EMF exposure to human bodies (female and child) in terms of the specific absorption rate (SAR) and the temperature rise caused by the EMF absorption in body tissues and the resultant dielectric heating. In particular, we determined 1g and 10g mass-averaged SAR, the whole body averaged SAR, and temperature rise values inside the human whole-body and body parts. The compliance of the results with the safety limits was also investigated according to international standards related to SAR and temperature rise.

Keywords— EMF, FDTD, SAR, Temperature Rise.

I. Introduction

In modern life, electronic devices that emit electromagnetic fields (EMFs) are becoming increasingly prevalent. As the number of mobile phone users grows, so does the number of base stations, which in turn raises the EM background (frequency range: 100 kHz to 6 GHz). This ever-increasing EM background can interfere with the proper functioning of these devices. A high electromagnetic (EM) background is undesirable for the optimal operation of electronic systems and may pose a potential risk to human health. The high-value EMFs can disrupt the functioning of implanted medical devices and, in severe cases, may even be life-threatening to patients [1, 2]. On the other hand, ensuring a high-quality connection is essential for the proper operation of mobile phones. When the connection is weak, devices automatically increase their transmission power, which can adversely affect both nearby biological objects and electronic devices [3-6]. Additionally, there are many other sources of EMFs, and it is crucial to monitor these, as the rapid increase in the EM background could lead to uncontrollable processes in the near future. EMFs emitted by base stations and Wi-Fi systems into the environment continuously affect people and all living systems, as these devices are constantly active day and night. It is important to note that safety guidelines stipulate a maximum exposure duration of 30 minutes in areas where EM levels exceed permissible limits [7].

Given the above, there is increasing concern about the cumulative effects of long-term EM exposure.

Wi-Fi frequencies operate within the 2.4 GHz, 5 GHz, and 6 GHz ranges. While radiofrequency EM radiation does not possess sufficient energy to break chemical bonds, it can still have significant effects on biological systems [8]. RF waves are different from stronger (ionizing) radiation such as X-rays, gamma rays, and ultraviolet (UV) rays. Ionizing radiation can break the chemical bonds of DNA, which can cause cancer or serious health problems [9].

The impact of the EM field on living organisms is manifested in the form of biological (non-thermal) and thermal effects. Non-thermal effects mean some changes taking place at the cellular level and thermal effect refers to dielectric heating of tissues/temperature increase. In most cases, biological and thermal effects influence each other and might appear simultaneously. However, separate studies are needed for the estimation of effect size. To estimate the EMF exposure to biological organisms, the Specific Absorption Rate SAR [W/kg] is a parameter showing what part of the radiated RF energy is absorbed by the unit mass of a living body per unit of time [9]:

$$SAR = \frac{\sigma |\vec{E}|^2}{\rho}$$

where σ is material electric conductivity, E is electric field, and ρ is mass density.

Existing recommendations have two types of limits: basic limits, which must always be adhered to, and additional limits that apply to specific conditions and may be adjusted in certain cases. The primary limits are expressed through quantities that are not directly measurable but characterize the body, such as the Specific Absorption Rate (SAR). Safety requirements and recommendations are primarily based on standards set by organizations such as the WHO, IEEE, and ICNIRP [10-12]. To date, there are no specific guidelines or recommendations for protecting other living organisms from radiofrequency radiation besides humans. Scientifically, it is not possible to definitively assert that adhering to EM field limits will fully safeguard humans from potential long-term adverse effects. However, maintaining EM field values below established thresholds can help mitigate health risks. According to research findings, radiofrequency

electromagnetic fields (RF-EMFs) are classified by the International Agency for Research on Cancer (IARC) as "possibly carcinogenic to humans" [13]. However, scientists still have not reached a firm conclusion regarding the classification of RF-EMF as a possible carcinogen.

Based on the above, the aim of this research is to investigate the thermal effects caused by electromagnetic field (EMF) exposure to humans at 2.4 GHz Wi-Fi frequency using numerical simulations on the adult (female) and child heterogeneous models. We will determine SAR and temperature rise (ΔT) values, which will allow us to evaluate the possible biological effects. Based on the obtained results, a comparative analysis will be conducted.

Despite numerous studies in this area, the rapid advancement of technology means that the effects of EM fields on humans are not yet fully understood and require further research.

II. METHODOLOGY

To study RF-EMF exposure in humans using numerical simulations, the finite difference time domain (FDTD) method was used. The FDTD method remains a powerful tool for understanding the interactions between EMFs and biological tissues. FDTD can handle complex, non-uniform shapes, making it suitable for modeling the human body, which has intricated anatomical features and varying tissue properties. It simulates how EMFs interact with the human body, including penetration, reflection, and absorption of EM waves. The FDTD method discretizes both space and time into a grid. The computational domain is divided into a series of small cells, and time is divided into discrete steps. The core of the FDTD method is solving Maxwell's equations, which describe how electric and magnetic fields propagate. The equations are solved iteratively at each grid point over time. The method uses finite difference approximations to update the electric and magnetic field values from one time step to the next. This involves alternating between solving for the electric and magnetic fields [14]. By integrating with thermal models, FDTD also helps in understanding the thermal effects of EMF exposure, including potential heating of tissues.

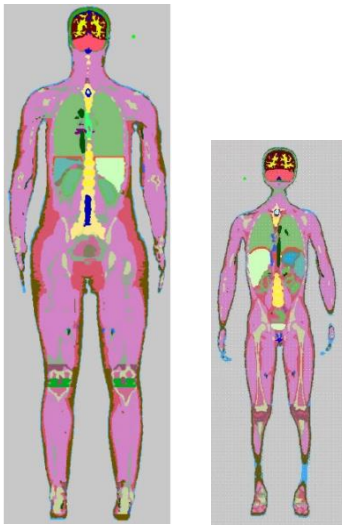
For our research, we used the FDTD-based software package FDTDLab (Tbilisi State University, Tbilisi, Georgia) to conduct EM and thermal simulations and determine SAR and temperature rise in human tissues. In FDTDLab, as with other FDTD-based software, the EM solver relies on the numerical solution of Maxwell's differential equations using the FDTD technique and the Yee algorithm [14, 15], and the thermal simulation and analysis is based on Penne's bio-heat equation [16].

For numerical simulations, the heterogeneous realistic three-dimensional discrete models of a female named „Ella" and the child model „Thelonious" from the Virtual Population (IT'IS Foundation, Zurich, Switzerland) were used as human models. The characteristics of these models are presented in Table 1. The Virtual Population (Vip) is a collection of high-resolution and detailed anatomical models of the human body. Both selected human models consist of up to 80 different types of tissue and have a 2 mm resolution in our simulations (Fig. 1). Frequency-dependent EM parameters and thermal parameters of tissues were selected from the IT'IS Database of tissue properties [17].

The EMF source represents a sinusoidal plane wave (far-field exposure) at 2.4 GHz. Fig. 2 shows three directions (front, back, and left) and six E-field polarizations (two orthogonal polarizations for each direction) of the incident plane waves, which are the same for both human models.

TABLE I. USED HUMAN MODELS WITH DIMENSIONS AND CHARACTERISTICS

Human Models	ELLA	THELONIOUS
Sex	female	male
Type	young adult	child
Age [Years]	26	6
Height [m]	1.63	1.15
Weight [kg]	57.3	18.6
BMI [kg/m²]	21.5	14.1



(a) (b)

Fig. 1. Discrete human body models (a) female (Ella) and (b) child (Thelonious) in the XOZ plane. The grid step is 2 mm.

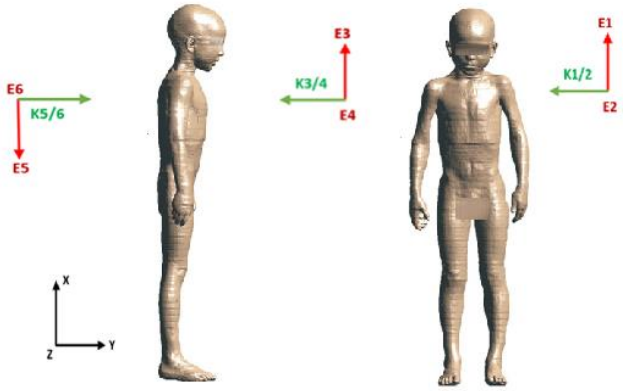


Fig. 2. Considered directions of incident plane waves and E-field polarizations.

For the thermal calculations, the initial temperature of all human body tissues was 37 ^{0}C, and the temperature of the air – was 22 ^{0}C. The convection coefficient between the skin and external air was h = 8.

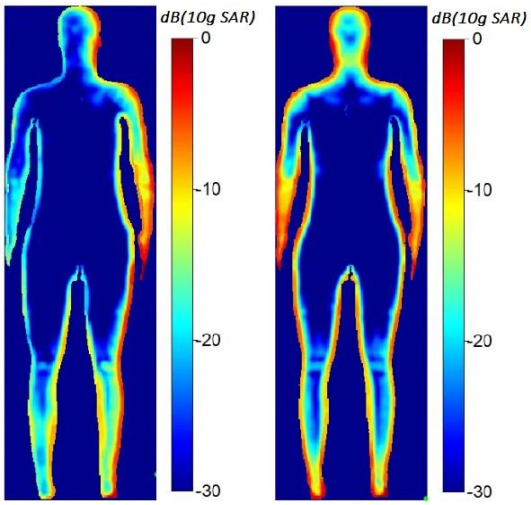
At first, we conducted EM simulations and estimated the absorbed EMF energy inside the woman and child's body tissues, quantified by SAR. Then, were performed thermal simulations in two stages: 1) evaluating the temperature in the body tissues in a steady state (without EMF exposure) and 2) evaluating the temperature during EMF Exposure (using SAR) and determined the difference between them, which is temperature rise (ΔT) caused by EMF absorption.

According to international safety standards, the maximum SAR limit is 2.0 W/kg averaged over 10 grams of tissue (ICNIRP), and 1.6 W/kg, averaged over 1 gram of tissue in the USA (FCC). The temperature increase should not exceed 1 ^{0}C [10-12].

III. Results of Numerical Simulations

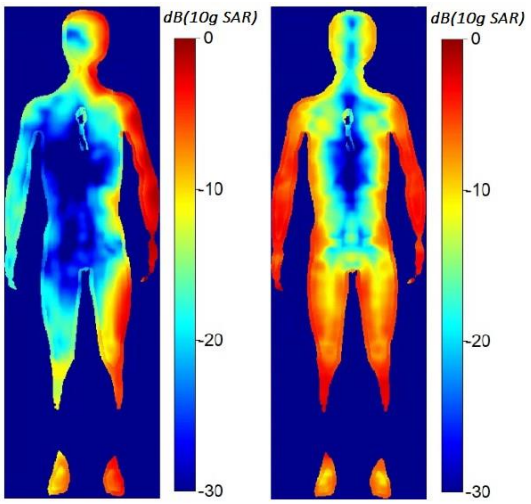
A. Results of EM Simulations

Within this study, we have conducted 6 EM simulations (1 frequency × 6 polarizations) for each human model (woman "Ella" and child "Thelonious") and determined SAR_{1g}, SAR_{10g}, and whole-body averaged SAR (WBA-SAR) inside the body tissues. All obtained results were normalized to the incident plane wave's power density of 10 mW/cm ^{2}.



(a) (b)

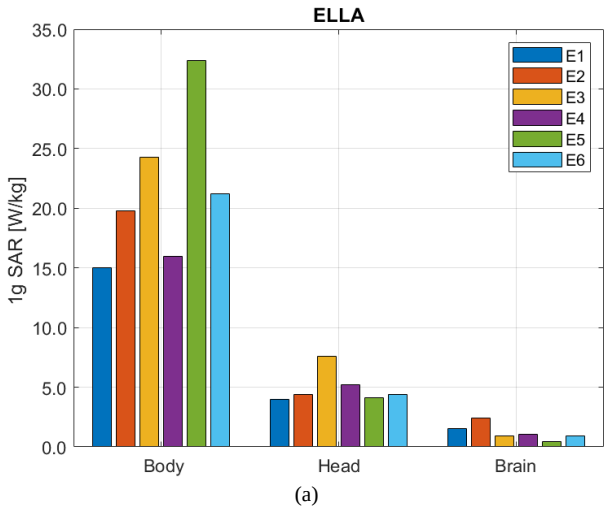
Fig. 3. SAR_{10g} distribution inside the Ella model for the incident plane wave (a) E2 and (b) E4 polarizations at 2.4 GHz. SAR_{10g} values on the ruler are given in W/kg using a logarithmic (dB) scale.



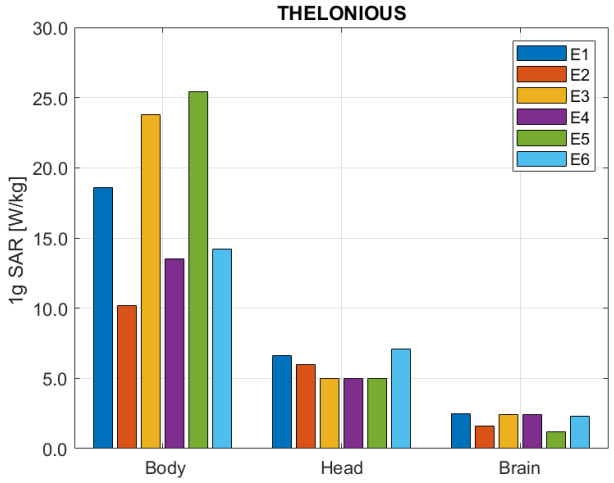
(a) (b)

Fig. 4. SAR_{10g} distribution inside the Thelonious model for the incident plane wave (a) E2 and (b) E4 polarizations at 2.4 GHz. SAR_{10g} values on the ruler are given in W/kg using a logarithmic (dB) scale.

Fig. 3 and Fig. 4 show the 10 g SAR distribution inside the Ella and Thelonious models when the E-field is directed orthogonal to the longitudinal axis of these models in the cases of incidence of plane waves from left and front sides (polarizations E2 and E4). Examination of the distribution of SAR_{10g} (Figs. 3 and 4) in the Ella and Thelonious models shows that the EMF absorption for the considered E-field polarization is comparatively higher in the limbs than in the head and brain. By comparing the SAR distribution for Ella and Thelonious, we see that the E-field penetrates deeper into Thelonious's body. This is due to the fact that a child's body size is smaller compared to a woman's body, and the 12.5 cm wavelength for 2.4 GHz is closer to the dimensions of a child's body parts. As is clearly seen from the results, the SAR values also significantly depend on the E-field polarization and body peculiarities. SAR values also depend on many factors that affect how the body tissues absorb EMF energy. SAR dependence on the frequency and polarization of the emitted EMF is studied in [18].

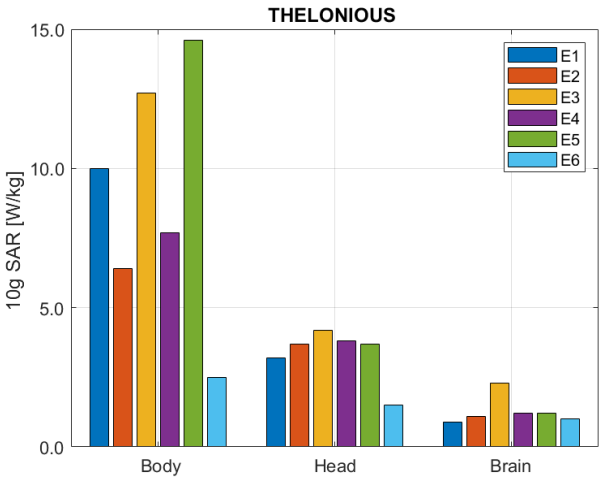


(a)



(b)

Fig. 5. Peak SAR_{1g} values for the: (a) Ella and (b) Thelonious whole body, head, and brain at 2.4 GHz. SAR_{1g} values are normalized on the incident power density of 10 mW/cm².

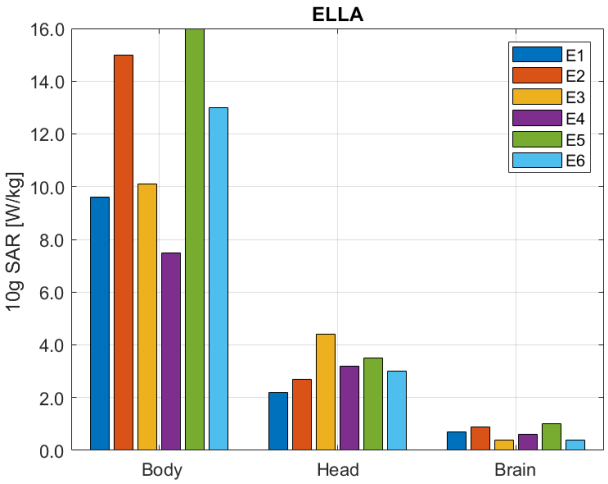


(b)

Fig. 6. Peak SAR_{10g} values for (a) Ella and (b) Thelonious models at 2.4 GHz frequency. SAR_{1g} values are normalized on the incident power density of 10 mW/cm².

Fig. 5 and Fig. 6 show peak SAR_{1g} and SAR_{10g} values for the Ella and Thelonious whole bodies, heads, and brains.

For both models, the SAR values are almost twice as high for the body as for the head and significantly higher than for the brain. As can be seen from these figures, the SAR_{1g} and SAR_{10g} values inside the child's brain are almost twice as high as in an adult woman's brain. As is known, the brain of a developing child is vulnerable to EM radiation; the thickness of the skull of adults reaches 2-6 mm, and its diameter is large compared to the skull of a child. The thickness of the skull of a 5-6-year-old child is about 0.5 mm, and by the age of 10, it reaches almost 1 mm [19]. That is why the EMF penetration depth into a child's head is much higher than that of an adult.



(a)

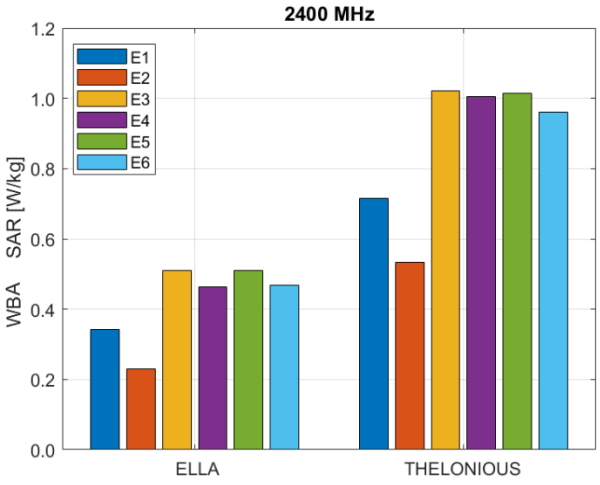


Fig. 7. WBA SAR values for Ella and Thelonious models at 2.4 GHz.

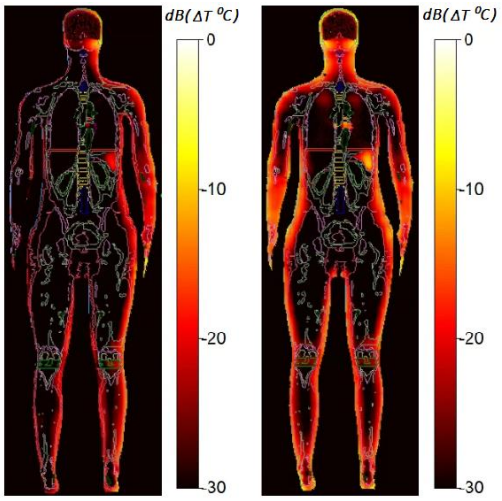
All of the peak SAR_{1g} and SAR_{10g} values for the whole body and the head exceed the SAR limits internationally for the incident plane wave's power density of 10 mW/cm^2.

Fig. 7 compares the WBA SARs for Ella and Thelonious, which also exceed the WBA SAR limit of 0.08 W/kg for all considered E-field polarizations. These values are also higher for the child compared to the woman.

B. Results of Thermal Simulations

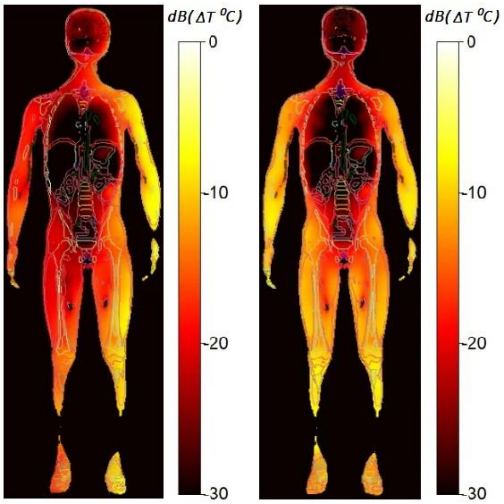
The results of thermal simulations, temperature rise distributions, and temperature rise values for Ella and Thelonious are presented in Figs. 8-10. The temperature rises distributions (Figs. 8 and 9) show the same tendency observed for the SAR distributions for both human models. It depends on E-field polarization and human body peculiarities.

Research was conducted at TU Ilmenau (Germany) within the - Funding programme/-ID: Joint Rustaveli-DAAD-fellowship programme, 2024 (Funding programme N. 57735997); Personal ref. N. 91852390; Grant Agreement N. 04/05, 16.05.2024.



(a) (b)

Fig. 8. Temperature rise (ΔT) distribution in the Ella model for the incident plane wave (a) E2 and (b) E4 polarizations at 2.4 GHz. ΔT values on the ruler are given in ^{0}C using a logarithmic (dB) scale.

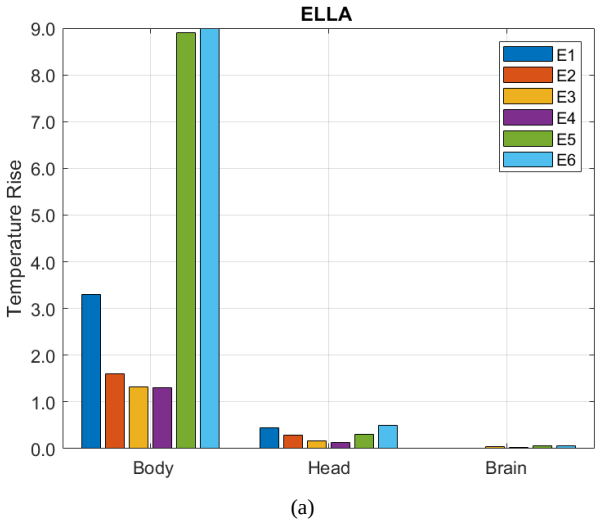


(a) (b)

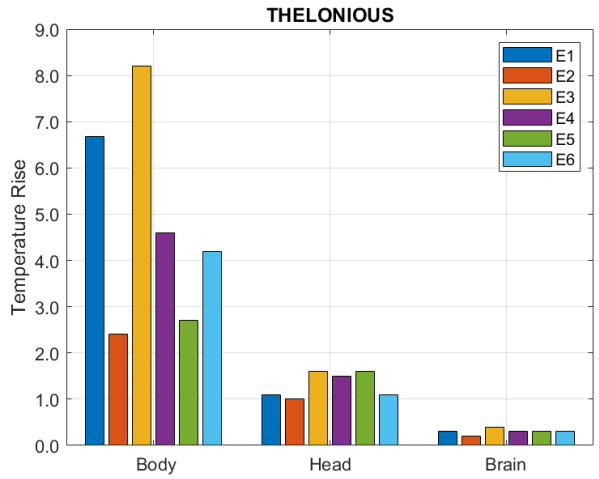
Fig. 9. Temperature rise (ΔT) distribution in Thelonious model for the incident plane wave (a) E2 and (b) E4 polarizations at 2.4 GHz. ΔT values on the ruler are given in ^{0}C using a logarithmic (dB) scale.

Apparently, the primary thermal reaction in the human body occurs in the skin and scalp. Since the RF-EMFs at a frequency of 2.4 GHz have a wavelength of 12.5 cm, it does not penetrate deeper into the woman's head, but in the case of a high reactive EMF, temperature increase in the brain tissues might be significantly higher [20]. Similar to SAR values, human body temperature response depends on various factors, such as the thermal properties of human tissues, as well as the characteristics of EMF sources [20], etc.

The temperature rises values for Ella and Thelonious inside the whole body, head, and brain for all considered polarizations are presented in Fig.10.



(a)



(b)

Fig. 10. Temperature rise (ΔT) for the: (a) Ella and (b) Thelonious models at 2.4 GHz for the incident power density of 10 mW/cm².

The obtained results have shown that ΔT values significantly depend on the E-field polarization (Figs. 9 and 10). It should be noted that in the case of the E5 and E6 field polarizations, the ΔT value in the woman's body is significantly higher compared to the other E1, E2, E3, and E4 field polarizations. Besides the E5 and E6 polarizations, the temperature rise values are higher for the child model compared to the woman. The measured ΔT values exceed internationally accepted limits of 1^0C for the woman and child's whole bodies and child's head. However, specifically for brain tissue the values are not higher than 0.5^0C for both human models.

Although high-frequency EMFs are mainly absorbed in the superficial tissues such as the skin, attention should be paid to the duration of exposure. This is because humans and all living systems are continuously exposed to EMFs. Therefore, even if the SAR and temperature rise values are within the prescribed limits, the long-term effects remain uncertain. It is important to note that animal studies on EMF exposure have shown brain cancer effects, which proves the classification of RF EM fields as possible carcinogens [18]. It should be noted that people living near an EM source are constantly exposed to EMFs and, in many cases, are unaware of the possible negative/unwanted effects. The ICNIRP guidelines adopted by the WHO do not account for variations

in human gender and age. Current standards are designed to protect against short-term harm based on existing knowledge, but long-term effects remain difficult to assess. The risk is further amplified at 5G frequencies [22-24]. When evaluating the effects of EMFs on humans, numerous factors must be considered, such as the complex anatomy and geometry of the human body, the context of use (e.g., inside a car or a closed room), the transparency of room walls, and phone grabbing configurations [25]. It's impossible to take into account all these circumstances, but their significance should be recognized.

IV. CONCLUSION

The thermal effects caused by human exposure to Wi-Fi frequency (2.4 GHz) EMFs were studied based on the determination of the SAR and temperature rise (ΔT) values, which assessed possible biological effects.

Based on the obtained results, the SAR and the temperature rise values caused by EMF absorption in human tissues exceed the established safety limits for the incident power density of 10 mW/cm² for the woman and child whole-body and head. These values are within the safe limits for brain tissue. It should be emphasized again that humans are continuously exposed to RF-EMFs. Obviously, it is impossible to completely avoid EM radiation, but keeping exposure within recognized safety limits can help mitigate potential health risks. Children, in particular, are a vulnerable group; their developing bodies are more susceptible to EMFs, and any adverse effects may be more pronounced [24]. Additionally, individuals with compromised health are also at increased risk.

Despite extensive research, the rapid pace of technological advancement means that the full impact of EM fields on human health remains not entirely understood and is still a subject of ongoing debate [23]. Therefore, further research in this area is essential.

ACKNOWLEDGMENT

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