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Implications of mmWave Radiation on Human Health: State of the Art Threshold Levels

RAVILLA DILLI
Manipal Academy of Higher Education, Manipal Institute of Technology, Manipal 576104, India
e-mail: dilli.ravilla@manipal.edu

ABSTRACT millimeter (mmWave) frequencies are covering from 30GHz to 300GHz in the electromagnetic spectrum and their uses in various applications like next-generation wireless communication systems (massive 5G telecommunications network), medical devices, airport security and automatic collision avoidance systems are growing vastly in the near future. Therefore, it is important to study the effects of mmWave radiation (non-ionization radiation) on biological systems and biophysical mechanisms. This paper focus on thorough review of nascent literature about current understandings of biological effects and epidemiological studies due to mmWave radiation in human beings. It presents latest guidelines with quantitative electromagnetic field thresholds by considering the realistic exposure scenarios of ''general public'' and ''occupational'' who undergo through wireless communication sources in their daily life. It also gives necessary safety measures to be taken while using the emerging mmWave technologies for future generation wireless communication networks.

INDEX TERMS 5G, electromagnetic fields, epidemiological studies, mmWave, next-generation wireless networks, non-ionization radiation, wireless communication systems.

I. INTRODUCTION

The RF EMFs are increasingly being identified as health and environmental pollution. It is very essential to have rigorous study on exposures to RF EMFs used in advanced wireless communication technologies, exposure standards and current scientific literature on human health implications [1]. The recent studies suggest to investigate all kinds of risks to human health and environment due to RF frequencies used in 5G implementations [2]–[5].

Extensive research present in literature include WHO (2014) technical documents on ''RF EMF exposure and health'' [6], [7], reports of ''SSM (2015, 2016, 2017, 2018)'' [8]–[11] and ''SCENIHR (2015)'' [12] give the relationship between EMF exposure and health effects like sleep quality, headaches, cognitive function, cardiovascular effects, difficulty in concentrating, etc. Addition to these, the recent researches are included to define guidelines by deriving the relation between biological effects and health of a human body [3], [13], [14].

Exposure to mmWave frequencies may cause direct and indirect adverse health effects. Direct effects are due to direct interaction of EMF with in the body and indirect effects include the interactions of a human body with objects that are at different electric potential. The health effects can be short-term or immediate for example stimulation of muscles, nerves, touching of conducting objects lead to shock or burn, energy absorption due to EMF exposure causes increase in tissue temperatures. The long-term effect of EMF exposure may lead to increased cancer risk. For frequencies <10GHz as shown in figure 1, the absorption of EM energy by human body is local and non-uniform.

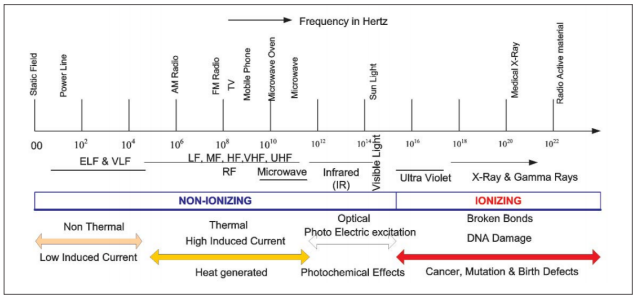

FIGURE 1. EM wave spectrum.

mmWave frequency bands cause NIR as the photon energies are too weak to remove an electron from an atom. However, NIR of mmWave frequencies can lead to biological effects in human body like inducing electrical current in cells as well as tissues, changing regular chemical reactions in body, and generate heat.

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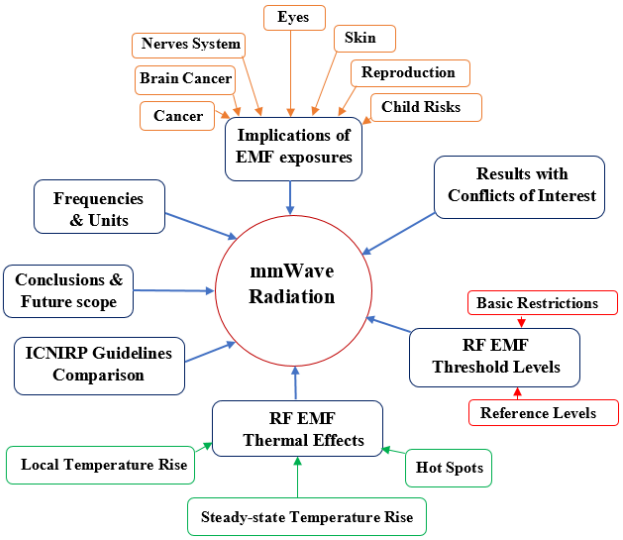

FIGURE 2. Effects of millimeter (mmWave) radiation on human health.

The rest of this paper is organized as follows. In Section II, dosimetry quantity and SI units are defined to measure RF EMF Exposures for frequencies up to 300GHz. In Section III, the effects of various human body parts exposure to RF EMFs and their health implications are summarized. Section IV highlights the interesting outcomes of various studies on RF EMFs which indicate no adverse health effects on human beings. Section V defines the latest assessment guidelines based on laboratory results and epidemiological studies mentioned in section III and section IV. In Section VI, study on thermal effects due to RF EMF exposures on human body are presented and threshold levels are defined to protect from EMFs. In Section VII, the EMF thresholds as per ICNIRP (1998) are compared with the latest guidelines of ICNIRP (2020). Section VIII concludes the mmWave radiation effects on human body as shown in figure 2 and highlights the EHS disorders as future scope.

II. FREQUENCIES & UNITS

Dosimetry calculations and measurements are needed to assess the absorbed EM energy by human body due to high frequency EMFs. Quantities to measure the amount of radiation absorbed by human organs are depending on the frequency range [15]. At mmWave frequencies, dosimetry quantity for human exposure to RF EMFs changes from SAR to ''incident power density''.

For frequencies $<$10GHz, entire-human body average SAR and local SAR are useful quantities to measure effects of exposure to EMFs and they are depending on: incident field values (frequency, polarization, source-object are in near field or far field), exposed body characteristics (internal and external geometry, size, dielectric properties of tissues), reflectors, and ground effects around the exposed body. For frequencies $>$10GHz, absorption of EM energy occurs at surface of human body as the depth of penetration of EM field into tissues is small. Temperature elevation in a multi-layer human head model was investigated using beam-steering

TABLE 1. Quantities and corresponding SI Units to measure RF EMF Exposure.

Frequency rage	Dosimetry Quantity	SI Units
$<$ 10MHz	Current density	A/m^2
10MHz-110MHz	Current	Ampere
10kHz-10GHz	SAR	W/Kg
300MHz-10GHz	SEA	J/Kg
10GHz-300GHz	Power Density	W/m^2

diploe antennas, plane waves, and patch antenna arrays at 28GHz carrier frequency and correlated with power density metrics. The results suggest that spatial average power density over 1cm^2 is a suitable metric to measure peak temperature elevation [16]. Table 1 shows the useful quantities to measure RF EMF exposures at various frequency ranges.

III. IMPLICATIONS OF EXPOSURES TO RF EMF

In this section, the effects of various human body parts exposure to RF EMFs and their health implications are summarized. Research on RF EMF emitted by MSs that use frequencies up to 6GHz is conducted through an interdisciplinary collaboration of engineers, biologists and doctors, who are professionals in handling protection of biosphere against negative effects of RF EMF over many years. The outcomes of this rese\arch provided evidence for WHO to classify RF EMF as factor for carcinogenic to human beings [17]. There can be two types of indirect EMF coupling: 1) contact currents due to contact of human body with objects of different potential, 2) currents due to medical devices implanted in or worn by an individual. These indirect effects are depending on size of objects, frequency, size of human body, are of contact. Exposures to RF EMFs at 2GHz-120GHz frequencies showed that 10% rise in incident power density leads to 3-370% increase in absorbed power for frequencies $\geq$6GHz [18].

A. CANCER

Most of the epidemiological and experimental studies has focused on RF EMF exposure in wireless mobile communications, and cancer. Laboratory vitro studies established the relation between RF EMF exposure and adverse biological effects in humans including various types of cancer and DNA damage [19]. A review of epidemiological and experimental studies due to RF EMF exposure in children on their cognition, incidence of leukaemia and brain tumors reveals the evidence for assumption that RF EMF exposure can leads to adverse health hazards [20]. The association between increased childhood leukaemia incidences and mortality with proximity to TV towers was investigated [21]. Among all malignancies of hematopoietic or lymphatic systems, the differences in morbidity rates between RF EMF exposed and non-exposed humans were found for chronic myelocytic leukaemia is 13.9%, acute myeloblastic leukaemia is 8.62% and non-Hodgkin lymphomas as 5.82% [22].

The outcome of all these research studies reported that long-term usage of MS increases slight risk of brain tumors

and exposure to RF EMFs at mmWave frequencies causes carcinogenesis [23]. IARC Monographs gives an evaluation of carcinogenic hazards associated with exposure to RF EMFs due to 30kHz-300GHz frequencies. It has been reviewed the epidemiological research evidence, cancer bioassays, mechanistic data and concluded that possible carcinogenic [24], increased risk of glioma (a malignant brain tumor) leads to brain cancer among people with higher usage of MSs [25]–[27].

B. BRAIN CANCER

There can be mainly two biological effects in human body due to RF EMF exposure: variations in permeability of membranes, rise in body temperature. The consistent research outcome of many researches is the effect of RF EMF exposure on brain activity and it is measured by EEG. There exists a small and unclear effect on brain functioning due to EMF exposure.

Temperature elevation in a human head for occupational exposures due to RF EMFs at 3GHz-10GHz frequencies are investigated using SAR over 10gram tissues as metric. Maximum temperature elevation observed on brain periphery and at high intensity RF EMFs temperature reaches 40°C at SAR of 100W/kg which falls in the current limits [28]. The excessive exposure to RF EMFs over long durations cause DNA damage and increase the risk of brain cancer in humans as well as animals. Children are highly susceptible to RF EMFs in terms of hyper conductivity of brain tissues [29].

C. HUMAN NERVES SYSTEM

Relation between usage of MSs and risks for various diseases of CNS was investigated, results of the experiment demonstrates that excesses of migraine and vertigo observed in people with excessive usage of MSs [30]. RF frequencies used in industrial, medical, communications including MSs directly exposes human brain and produce biological effects on CNS. Reactions of CNS and cardiovascular effects may lead to Alzheimer's diseases, pathophysiology of CNS disease [31]–[33].

RF EMF can induce changes in CNS nerve cells that includes neuronal cell apoptosis, changes in function of nerve myelin and ion channels; RF-EMF causes stress in living creatures. The effect of RF EMFs due to BSs, MSs, Wi-Fi modems on blood glutathione S transferase and antioxidant activity [34] and red blood cells exposed to RF EMFs at 18GHz frequencies demonstrates that induced EMFs rotate water molecules and cause disturbance of membrane [35].

D. HUMAN EYES

The adverse health effects due to non-ionizing, non-visible RF radiation are emphasized based on laboratory experiments and it cause adverse systemic effects including damages of skin and eyes [36]. Variations in SAR and temperature rise at GHz plane-wave EMF exposure effects human eye like changes in palpebral fissure, extent of opening between eyelids and maximum temperature rise in lens was observed as 0.8°C at EM intensity of 100W/m^2 [37]. Ocular damage due to RF EMFs exposures at 40GHz, 75GHz, and 95GHz frequencies were investigated and it is observed that after 10minutes from exposure to RF EMFs, ocular damage occurs including decrease in transparency and cornea thickness. The 50% probability of ocular damage was higher at 40GHz, 95GHz and 75GHz respectively for given incident power densities [38]. Ocular damage and healing due to RF EMFs exposures at 162GHz were investigated, and results show that 10%, 50%, 90% probability of ocular damage was occurring at 173mW/cm^2, 252mW/cm^2, 368mW/cm^2 of incident power densities respectively and 9days are needed to subsidize to normal [39].

E. HUMAN SKIN

Experiment on dielectric properties of skin (dermis & epidermis) conducted for 500MHz – 110GHz frequencies in comparison with Gabriel's data using parametric expansion [40] and the results indicate that skin temperature elevation is dominant at higher frequencies [20]. EMF exposures at 18GHz frequencies over a one-hour period induced periodic inconsistency increases in the cell growth behavior [41].

F. HUMAN REPRODUCTION, PREGNANCY, AND CHILD RISKS

Exposure to RF EMFs of MSs may lead to potential influence on early spontaneous abortions [42]. Study of reproductive hazards after exposure to RF EMF showed that 23.5% of children born by the RF EMF exposed mothers were boys and RF EMF was also associated with low birth weight, but only for male newborns [43]. The excessive exposure to RF EMFs over long durations causes harmful effects on female & male reproduction, ''idiopathic environmental intolerance'' in humans as well as animals. Children are highly susceptible to RF EMFs in terms of nervous system development [28]. The prenatal and postnatal exposure to RF EMFs affects cognitive, emotional outcomes, and hearing in children [29], [44]–[46]. The review summarizes information available on all possible effects of RF EMF on reproductive health system [19].

IV. RESULTS WITH CONFLICTS OF INTEREST

In this section, interesting outcomes of various studies on RF EMFs are summarized which indicate no adverse health effects on human beings. Dosimetry simulations are conducted on various regions of human head to measure RF EMFs at 835MHz-1.9GHz frequency range and there was uncertainty of head morphology to RF EMF exposures [47]. The experimental results of non-thermal biological effects at cellular and molecular level induced by 2.45GHz EMF exposures did not induce any significant biological effects [48]. Exposure to RF-EMFs generated by BSs and their impact on cognitive functions show that exposure of human lymphocytes to 900MHz frequencies used in MS for 30minutes does not significantly impact DNA integrity [49], [50]. ''Embryonic zebrafish'' model is used to assess the RF EMF exposure of 3.5GHz frequency band on biology and

the results revealed no significant impacts on mortality or morphology response [51].

Vivo, vitro studies on human health at 6GHz-100GHz did not give any consistent relationships between human health and RF frequencies used, duration of exposure, power density and exposure effects [52]. The fear of adverse effects from exposure to RF EMF in the presence of BS was investigated and shown the relation between headaches, perceptual speed to measured power density; and no significant effect was found on sleep quality [53]. Electroencephalogram of humans who are exposed to RF EMF have been noted while they are walking and sleep states. The evidences of the study were failed to relate usage of MS with health implications [54]. Meta-analysis of epidemiological studies did not show increased risks for brain, pituitary, salivary gland tumors, and meningioma with usage of MS [55]. The findings of [56] did not prove the presence of acoustic neuroma health risk with long-term usage of MS. It is shown that there is no association between risk of early childhood cancers and estimates of mother's EMF exposure to MSs, BSs during pregnancy [57]. AGNIR (2012) review report on safety of RF EMFs describes conflict of interest, omissions, misleading statements and it is unsuitable for health risk assessment. Summary and overall conclusions of the report are not accurately reflecting the existing scientific evidences. It is essential for individuals, decision makers, organizations to have accurate information on RF EMFs to reach their safeguard responsibilities and protect [58]. In this section, we have summarized to answer all possible biological effects, health risks due to RF EMF along with conflicts of interest [59].

V. THRESHOLDS FOR RF EMF EXPOSURES

In this section, the assessment guidelines [60] are framed based on laboratory results and epidemiological studies mentioned in section III and section IV. These latest guidelines ensure that the 5G cellular standard maintains lower peak spatial powers and does not cause potential adverse health effects. The operational thresholds are defined [60] to achieve appropriate protection levels and they are based on the relations between primary effects of RF EMF exposure like ''heating'' and health effects like ''pain''. Reduction factors are applied to these operational thresholds to provide EMF exposure restriction values by considering biological variations in population like their age, sex, environmental variations like humidity, clothing, air temperature, uncertainty associated with health science and deriving EMF exposure values.

RF EMF exposure levels are defined separately for ''*general public*'' and ''*occupational*''. Most of the time, general public are not aware of EMF exposure and no steps are taken for reducing it. Human body is divided into two sets: ''*Torso & Head*'' and ''*Limbs*''. EMF exposure restrictions are defined separately and temperature rise should not be greater than 5°C, 2°C for each set respectively. To avoid health hazards and adverse EMF exposure, guidelines presented in [61], [62] are defined at two classes: basic exposure criteria (basic restrictions), reference levels, and they are applicable to both general public and occupational people.

A. BASIC RESTRICTIONS

These are the limiting conditions or thresholds of EMF exposure on established health effects of humans. One of the physical quantities among current density, power density, SAR are used to specify basic restrictions based on frequencies range. These restrictions are different for various parts of the human body, sources operating at far distances and sources operating very near to human body. These restrictions are defined for frequency range 100kHz-10GHz in terms of SAR to prevent localized human tissue heating and body heating stress, for 10GHz-300GHz frequency range, restrictions are defined in terms of power density to avoid excessive heating on surface of human body or in tissue. Study of tumor-promoting effects [63] suggests that for MS users, SAR values of 0.04W/kg & 0.4W/kg can be threshold levels for low and moderate exposures respectively.

Table 2 and Table 3 represent basic restrictions as per ICNIRP guidelines of the years 1998 and 2020 respectively for ''occupational'' as well as ''general public''. The EMFs include due to a non-pulse, pulse, train of pulses and total exposures over the time duration of 't' seconds. As the general public may not aware of EMF exposures and to reduce the risk, thresholds for general public are kept lower compared to occupational. At the time of defining guidelines as given in Table 1, there was more scientific uncertainty related to adverse health effects and dosimetry on human body. These uncertainties are reduced in the guidelines mentioned in Table 2. However, reduction factors are introduced while defining basic restrictions to compensate the uncertainties, variations in environmental conditions, thermal physiology and activities of people.

B. ENTIRE-HUMAN BODY SAR VALUES FOR FREQUENCIES 10MHz-300GHz

''Entire-human body'' average SAR values are equal to 4W/kg and they are measured over 30minutes time duration, exposed limits corresponding to OAHE thresholds for 1°C rise in core body temperature. The SAR and power density values measured for localized exposures averaged for 10gram cubic mass, 4cm^2 body surface area and 6minutes time duration. A reduction factors of 10, 50 are applied for occupational and general public exposures respectively. Therefore, average SAR values for occupational and general public becomes 0.4W/kg, 0.08W/kg respectively. The ''entire-human body'' average SAR levels for frequencies >6GHz is same as for frequencies <6GHz in as the temperature rise at higher frequencies are highly superficial.

C. LOCAL BODY SAR FOR FREQUENCIES <6GHz

Appropriate basic restrictions are defined to protect from localized tissue heating in human body due to near-and far-field exposures at 0.5GHz-6GHz RF EMFs. VAR is a suitable measure over 10cm^3 average volume than SAR over

TABLE 2. Basic restrictions for time varying RF EMF exposure averaged over ≥ 6minutes time interval [15].

Exposure Type	Range of Frequencies	Average SAR for entire-human body	SAR local to *"Torso & Head"*	SAR local to *"Limbs"*	Power Density
Occupational	10MHz-10GHz	0.4 W/kg	10 W/kg	20 W/kg	-
	10GHz-300GHz	-	-	-	50 W/m^2
General Public	10MHz-10GHz	0.08 W/kg	2 W/kg	4 W/kg	-
	10GHz-300GHz	-	-	-	10 W/m^2

TABLE 3. Basic restrictions for time varying RF EMF exposure averaged over ≥ 6minutes time interval [60].

Exposure Type	Range of Frequencies	Average SAR for entire-human body (W/kg)	SAR local to *"Torso & Head"* (W/kg)	SAR local to *"Limbs"* (W/kg)	Power Density (W/m^2)
Occupational	< 6GHz	0.4	10	20	-
	6GHz-300GHz	0.4	-	-	100
General Public	< 6GHz	0.08	2	4	-
	6GHz-300GHz	0.08	-	-	20

TABLE 4. Basic restrictions for time varying RF EMF exposure averaged over ≤ 6minutes time interval [60].

Exposure Type	Range of Frequencies	SEA local to "*Torso & Head*" (kJ/kg)	SEA local to *"Limbs"* (kJ/kg)	Power Density (kJ/m^2)
Occupational	< 6GHz	$3.6[0.05+0.95(t/360)^{0.5}]$	$7.2[0.025+0.975(t/360)^{0.5}]$	-
	6GHz-300GHz	-	-	$36[0.05+0.95(t/360)^{0.5}]$
General Public	< 6GHz	$0.72[0.05+0.95(t/360)^{0.5}]$	$1.44[0.025+0.975(t/360)^{0.5}]$	-
	6GHz-300GHz	-	-	$0.72[0.05+0.95(t/360)^{0.5}]$

10gram mass. At 6GHz frequency, incident power flux density is an appropriate metric [64].

"Local body SAR" value is 20W/kg averaged over 10gram cubic mass, 6minutes time duration as exposure limits corresponding to OAHE threshold for 5°C & 2°C temperature rise in "*Torso & Head*" (5°C for class-1 tissues, 2°C for class-2 tissues). A reduction factors of 2 and 10 are applied for occupational and general public respectively. Therefore, basic restrictions of $SAR_{10grams}$ for occupational and general public are 10W/kg and 2W/kg respectively. The reduction factors for local exposures are less than that of entire-human body exposures because the associated OAHE thresholds are loosely dependent on environmental conditions.

"Local body SAR" value is 40W/kg averaged over 10gram cubic mass, 6minutes time duration as exposure limits corresponding to OAHE threshold for 5°C temperature rise in *"Limbs"*. A reduction factors of 2 and 10 are applied for occupational and general public respectively. Therefore, basic restrictions of $SAR_{10grams}$ for occupational and general public are 20W/kg and 4W/kg respectively. The reduction factors for local exposures are less than that of entire-human body exposures because the associated OAHE thresholds are loosely dependent on environmental conditions.

D. LOCAL BODY APD FOR FREQUENCIES 6GHz-300GHz

"Local body APD" value is 200W/kg averaged over 4cm^2 body surface area, 6minutes time duration as exposure limits corresponding to OAHE threshold for 5°C temperature rise in *"Limbs"*, for 5°C & 2°C temperature rise in "*Torso & Head*" (5°C for class-1 tissues, 2°C for class-2 tissues). A reduction factor of 2 and 10 are applied for occupational and general public respectively. Therefore, basic restrictions of APD over 4cm^2 for occupational and general public are 100W/m^2 and 20W/m^2 respectively. For frequencies >30GHz, an additional restriction on EMF exposure is defined as the averaged APD over a 1cm^2 surface area of human body and it is limited to two times that of 4cm^2 restriction for both occupational and general publics.

Table 4 represents basic restrictions in terms of SEA and 't' is exposure duration in seconds to compute EMF due to a single pulse, pulse train or subgroup of pulse train. SEA local is averaged over 10gram cubic mass for 6minutes time duration. For frequencies less than 6GHz, SEA thresholds values are $7.2[0.05 + 0.95(t/360)^{0.5}]$ kJ/kg for "*Torso & Head*" exposure, and $14.4[0.025 + 0.975\ (t/360)^{0.5}]$ kJ/kg for "*Limb"* exposure. The reduction factors 2 and 10 are applied to occupational and general public respectively. Therefore, the local SEAs to "*Torso & Head*" exposure are $3.6[0.05 + 0.95(t/360)^{0.5}]$ kJ/kg and $0.72[0.05 + 0.95\ (t/360)^{0.5}]$ for occupational and general public respectively. Similarly, local SEAs to "*Limbs"* exposure are $7.2[0.05 + 0.95(t/360)^{0.5}]$ kJ/kg and $1.44[0.05 + 0.95(t/360)^{0.5}]$ for occupational and general public respectively.

E. LOCAL BODY AED VALUES FOR FREQUENCIES 6GHz-300GHz

To limit "temperature rise" less than OAHE thresholds for class-1 and class-2 tissues, AED values are defined over 4cm^2 body surface area for the duration of less than 6minutes.

For frequencies 6GHz-30GHz, threshold AED limit for "*Torso & Head*", "*Limbs"* is $72[0.05 + 0.95(t/360)^{0.5}]$ kJ/m^2. The reduction factors of 2 and 10 are applied for occupational and general public respectively. Therefore, threshold AEDs are $36[0.05 + 0.95(t/360)^{0.5}]$ kJ/m^2 and $7.2[0.05 + 0.95(t/360)^{0.5}]$ kJ/m^{2}for occupational and general public respectively. For frequencies 30GHz-300GHz the radiation beams are very focused, therefore an additional restriction is defined as threshold AED value over body average

TABLE 5. Reference levels for time varying RF EMF exposure during 6minutes average time interval corresponding to entire-human body average basic restrictions [15].

Exposure Type	Range of Frequencies	E-field	H-field	B-field	Power Density
Occupational	2GHz-300GHz	137 V/m	0.36 A/m	0.45 μTesla	50 W/m^2
General Public	2GHz-300GHz	137 V/m	0.16 A/m	0.20 μTesla	10 W/m^2

area of 1cm^2 for "*Torso & Head*", "*Limbs*" is 144[0.025 + 0.975(t/360)$^{0.5}$] kJ/m^2 [65]. The reduction factors of 2 and 10 are applied for "occupational" and "general public" respectively. Therefore, threshold AEDs are 72[0.05 + 0.95(t/360)$^{0.5}$] kJ/m^2 and 14.4[0.05 + 0.95 (t/360)$^{0.5}$] kJ/m^2 for occupational and general public respectively.

F. REFERENCE LEVELS

These are EMF exposure levels outside the human body and they are derived from basic restrictions under worst-case realistic situations. These levels for EMF exposure are derived from a combination of measurement, computational studies and defined for comparing practically measured physical quantity values. Magnetic flux density, magnetic field strength, electric field strength, power density, SEA, contact currents are some of the measured quantities for reference levels. In a given EMF exposure situation, these quantities are measured and compared with corresponding reference levels. Different assessment rules are framed to define reference levels based on RF EMFs lies in reactive near-field, far-field or radiative near-field. The reference level guidelines are more conservative than corresponding basic restrictions and they are defined by considering uncertainties in type of EMF source, physical dimension of EMF source, variations of EMFs in the space occupied by a human body. For frequencies between 2GHz-300GHz, physical quantities used to measure reactive near-field EMFs are insufficient to guarantee compliance with corresponding basic restrictions. In such situations, consent with basic restriction are used for assessment.

In some scenarios RF EMFs of the exposure are less than the specified reference levels but exceeds the corresponding basic restrictions. For these scenarios, the values of reference levels are reduced by an amount of difference between corresponding basic restrictions and tissue exposure. By doing this, we can avoid harmful health effects on human body. If the difference between corresponding basic restrictions and tissue exposure is small, then reference levels are retained as it does not cause adverse health effects. For example, if children of age about 3years are exposed to EMFs due to frequencies between 1GHz-4GHz for 30minutes, then SAR elevation is smaller than basic restrictions by 15-40%. However, this does not lead to temperature rise of more than 1°C in the core body therefore reference values are retained [66].

Reference levels are mentioned for various scenarios in Tables 5–8. Table 5 gives reference levels which are averaged over 6minutes interval and Table 6 gives reference levels which are averaged over a 30minutes interval corresponding to entire-human body average basic restrictions. Table 7 and 8 give reference levels averaged below a 6minutes and above 6minutes intervals respectively for entire-human body.

TABLE 6. Reference levels for time varying RF EMF exposure during 30minutes average time interval corresponding to entire-human Body average basic restrictions [60].

Exposure Type	Range of Frequencies	Incident power density
Occupational	2GHz-300GHz	50 W/m^2
General Public	2GHz-300GHz	10 W/m^2

In Table 6, for frequencies 2GHz-300GHz: (a) in the radiative near-field zone, or far-field zone: compliance is demonstrated if incident power density not crosses the reference levels (b) in reactive near-field zone, reference levels are not used to find compliance, therefore basic restrictions should be assessed. In Table 8, for frequencies < less than 6GHz: (a) for radiative near-field zones and far-field, compliance is demonstrated if peak incident power density over the projected entire-human body space not exceeds the reference levels (b) for reactive near-field zone: incident power density is not used to demonstrate compliance for frequencies >2GHz, reference levels are not used to determine compliance. Therefore, basic restrictions must be assessed. For frequencies 6GHz-300GHz: (a) for radiative near-field zone and far-field zone, compliance is demonstrated if incident average power density over 4cm^2 projected body surface space not exceeds the reference levels (b) in reactive near-field zone, reference levels are not used to determine compliance, therefore basic restrictions must be assessed. For frequencies 30GHz-300GHz, EMF exposure averaged over 1cm^2 projected human body surface should not cross twice that of 4cm^2 restrictions.

Development of 5G technologies that use frequencies >6GHz leads to frame new EMF restrictions to protect against excessive temperature rise in human body. The guidelines presented in [15] gives protection from EMF exposure over the entire-human body up to 6minutes. As per guidelines presented in [60], the quantity SAR can be used to define average EMF exposure restrictions over the frequencies <300GHz under basic restrictions where the body temperature rise is observed for 30minutes. The new guidelines [60] uses a quantity 'absorbed power density' for measuring local EMF exposure >6GHz of the body to satisfy basic restrictions. Average absorption cross-section of the human body is measured at 1GHz-12GHz frequencies, its values ranges from 0.15m^2 to 0.4m^2 for 1GHz-6GHz frequency range and it slowly increases for 6GHz-12GHz range [67].

5G technologies which use frequencies >30GHz are having higher degree of focused radiation beams. High intensity EMF exposures leads to increase in local tissue temperature excessively for duration < 6minutes over the frequencies >30GHz. The restrictions defined in [60] ensure that 5G technologies does not lead to high temperature rise for RF EMF exposures < 6minutes. The restrictions are defined in terms of SEA for frequencies < 6GHz and AED for frequencies > 6GHz.

TABLE 7. Reference levels for local RF EMF exposure averaged for < 6minutes corresponding to basic restrictions of entire-human body.

Exposure Type	Range of Frequencies	Incident energy density (kJ/m^2)
Occupational	2GHz-6GHz	$200 \times 0.36[0.05+0.95(t/360)^{0.5}]$
	6GHz-300GHz	$275/f_G^{0.177} \times 0.36[0.05+0.95(t/360)^{0.5}]$
	300GHz	$100 \times 0.36[0.05+0.95(t/360)^{0.5}]$
General Public	2GHz-6GHz	$40 \times 0.36[0.05+0.95(t/360)^{0.5}]$
	6GHz-300GHz	$55/f_G^{0.177} \times 0.36[0.05+0.95(t/360)^{0.5}]$
	300GHz	$200 \times 0.36[0.05+0.95(t/360)^{0.5}]$

Note: 'f_G' is frequency in GHz, 't' is time interval in seconds.

TABLE 8. Reference levels for local RF EMF exposure averaged for > 6minutes corresponding to basic restrictions of entire-human body.

Exposure Type	Range of Frequencies	Incident power density (W/m^2)
Occupational	2GHz-6GHz	200
	6GHz-300GHz	$275/f_G^{0.177}$
	300GHz	100
General Public	2GHz-6GHz	40
	6GHz-300GHz	$55/f_G^{0.177}$
	300GHz	20

Note: 'f_G' is frequency in GHz.

VI. THERMAL EFFECTS OF RF EMF

In this section, study on thermal effects due to RF EMF exposures on human body are presented and threshold levels are defined to protect from EMFs. Exposures to RF EMFs cause generation of heat in human body, therefore it is essential to keep the safe levels in order to overcome heat-induced adverse health impairments [68], [69]. To avoid significant temperature increase in human body, temperature thresholds are defined in terms of ''temperature rise'' instead of ''absolute temperature''. At reference levels defined in ICNIRP 1998 [15], a peak temperature rises of 1°C occurred for worst-case scenario. It suggests ''temperature rise'' as metric instead of ''local peak SAR'' to prevent excessive localized tissue heating, also take time of exposure into account while defining temperature rise [70]. Temperature thresholds are defined based on two parameters: steady-state temperature rise and brief-temperature rise. *Steady-state temperature rise:* It leads to slowly increase in temperature of a human body and it allows time for thermoregulatory processes to compensate rise in temperature and dissipate heat over the tissues. *Brief temperature rise:* It may not provide sufficient time for increased temperature to dissipate and it results in more temperature rises over small regions.

A. THERMAL EFFECTS DUE TO STEADY-STATE TEMPERATURE RISE

Increase in human body core temperature due to RF EMFs can cause adverse health impairments when temperature rise is above +1°C [71]. Threshold RF EMF exposure levels for frequencies below 6GHz under steady-state are defined as entire-human body average SAR of 4W/kg over half-an hour corresponding to 1°C rise in human body core temperature. Thermal distribution and cardiovascular changes were investigated in entire-human body exposures to RF EMFs at 35GHz. Power densities at 35GHz leads to entire-human body SAR of 13W/kg and it causes increase in heart rate and rapid temperature rise in skin [72]. It is proved that the depth of RF EMF penetration decreases with increasing frequencies and the thermal effects are more superficial compared to deep tissues, also heat removal from the body becomes simple as thermal energy transfer to environment

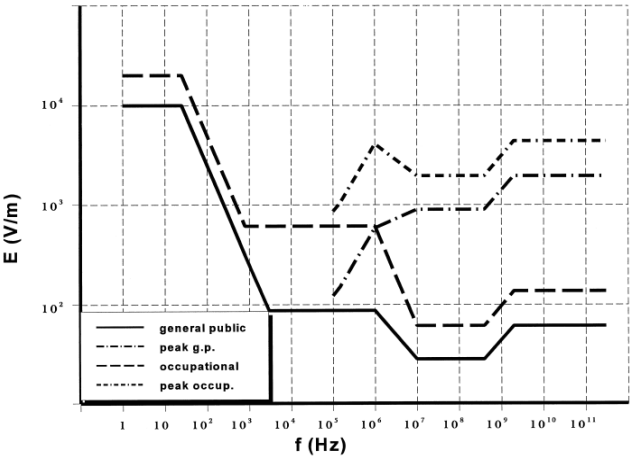

FIGURE 3. Reference levels for RF EMF exposure to time varying E-fields [15].

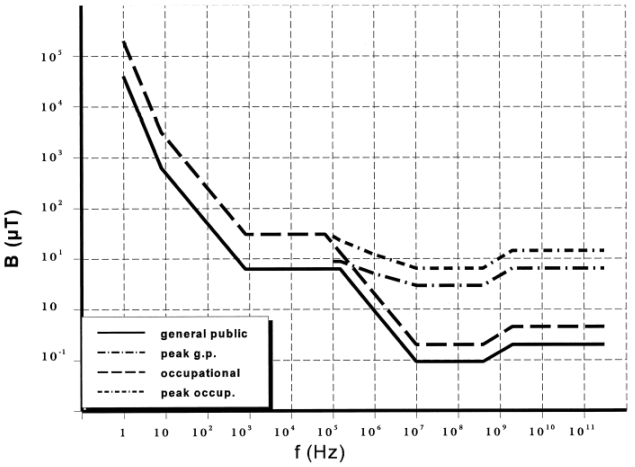

FIGURE 4. Reference levels for RF EMF exposure to time varying H-fields [15].

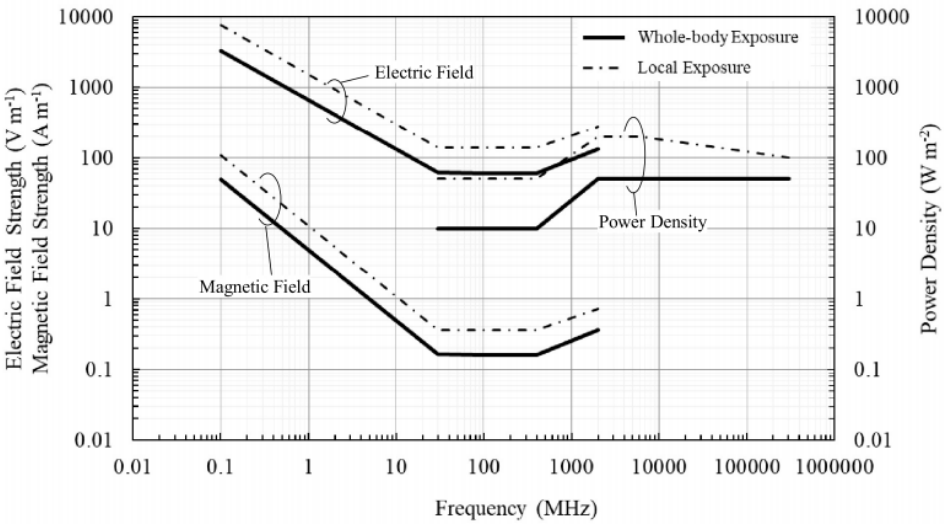

FIGURE 5. Reference levels for RF EMF exposure for "occupational" time averaged above 6minutes [60].

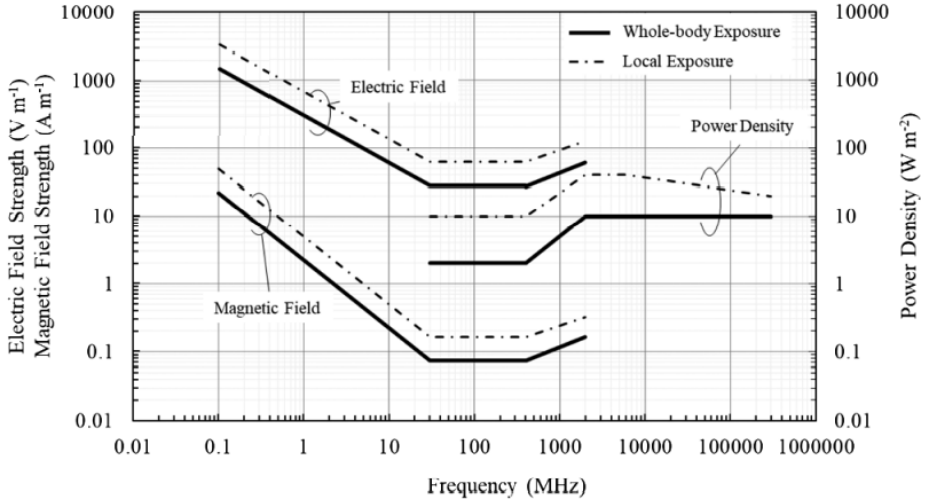

FIGURE 6. Reference levels of RF EMF exposure for "general public" time averaged above 6minutes [60].

is easier [73], [65]. For frequencies above 6GHz, RF EMF exposure causes heat mainly in the skin of human body [74]. At 6GHz and 300GHz frequencies, 86% of RF EMF exposures are penetrated within 8mm and 0.2mm depth from the skin surface respectively [75]. For frequencies above 300GHz, induced EMFs cause beyond 1°C temperature rise in human core body and it leads to severe health effects [76].

B. THERMAL EFFECTS DUE TO LOCAL TEMPERATURE RISE

Higher localized heats cause pain and cell damage in human body, however temperatures less than 42°C may not damage the cells [77]. Experiments conducted on human skin thresholds for thermal pain at 94GHz continuous wave frequencies result in skin surface temperature rises from 34°C to 43.9°C. Human skin exposure to RF EMFs cause heat in the skin and gives a threshold temperature of 43°C for pain [78]. Most of the literature about thermal thresholds of human body due to EMFs show that the temperature thresholds of 41°C-43°C beyond which there is likelihood of tissue damages and the severity of damage increases with exposed time [79]–[81]. We know that under normal thermal conditions, the human body temperatures are different at various body regions. According to the temperatures at different regions of the body, we can classify the tissues of human body into "*Class-1*" and "*Class-2*" tissues. These two classes are having different OAHE threshold levels [82]. Under normal thermal conditions, the typical temperatures of Class-1 tissues are 33°C-36°C and Class-2 tissues are less than 38.5°C [83]–[86]. Thermal thresholds for local temperature is defined as 41°C for safety beyond which likelihood of severe health effects occurs.

The OAHE thresholds for local temperature rise due to RF EMFs are 5°C and 2°C for Class-1 and Class-2 tissues respectively. For convenience, human body is divided into two regions: "*Torso & Head*" and "*Limbs*", these two regions are defined with different OAHE thresholds over

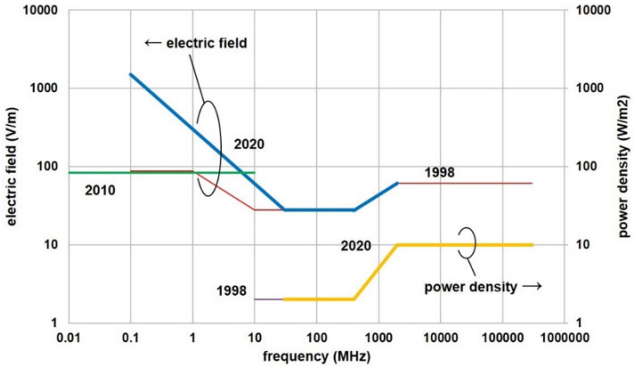

FIGURE 7. Entire-human body average reference levels for "general public" mentioned as per ICNIRP guidelines in the years 1998, 2010 and 2020 for 100kHz-300GHz frequency range.

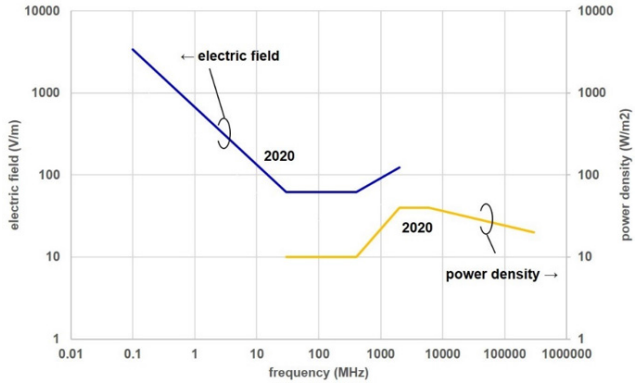

FIGURE 8. Reference levels for "general public" exposed locally for durations ≥ 6minutes over 100kHz-300GHz frequency range.

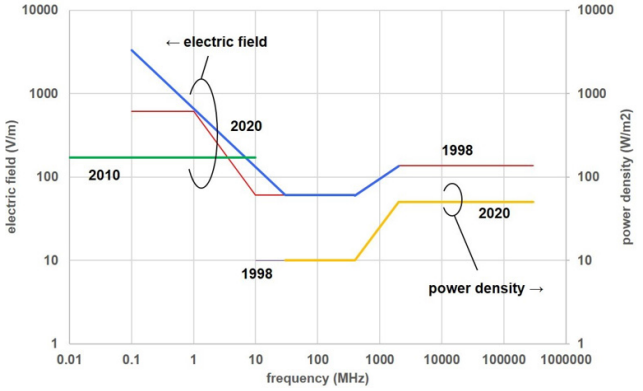

FIGURE 9. Entire-human body average reference levels for "occupational" as per ICNIRP guidelines given in the years 1998, 2010, and 2020 over 100kHz-300GHz frequency range.

10gram cubic mass as 2°C (or 5°C) and 5°C respectively. For frequencies less than 6GHz, OAHE thresholds are defined in regions "*Torso & Head*" and "*Limbs*" as 20W/kg and 40W/kg of SAR_{10g} respectively over a duration of 6minutes [73], [87]–[91]. For frequencies between 6GHz and 300GHz the induced EMF is mainly present on superficial tissues, therefore APD is a suitable quantity to measure the EMF. To set OAHE thresholds at 5°C for *Class-1* and 2°C for *Class-2* tissues local temperature rise, APD of 200W/m^2 is needed over an average area of 4cm^2 with duration of 6minutes [92], [93]. For frequencies from 6GHz to 30GHz, local temperature rise is measured over an average area of 4cm^2 [94]. For frequencies between 30GHz to 300GHz, the radiation beams diameter becomes smaller and smaller therefore the exposure over an average area is decreased to 1cm^2 and APD of 400W/m^2.

C. THERMAL EFFECTS DUE TO HOT SPOTS

Hot spots occur when there is sudden temperature rise on the tissues due to HTB and no sufficient time present for heat to dissipate. The effect of hot spots increases with higher frequencies as their penetration depth is very small [95]. To consider HTBs and maintain temperatures below OAHE thresholds, maximum exposure levels are treated as steady-state exposure levels and these are function of time.

VII. COMPARISON BETWEEN ICNIRP GUIDELINES FOR THE YEARS 1998 AND 2020

ICNIRP (1998) [15] allows E-field and H-field to use for entire-human body average reference levels over the frequency range 100kHz-300GHz as shown in figures 3 & 4 and it leads to potential inaccuracies for frequencies >2GHz in the near-field zone. ICNIRP (1998) [15] specify same reference levels for exposures in near & far field zones, however with new scientific research outcomes [60] defines separate reference levels in near & far fields as shown in figures 5 & 6. Figures 5 & 6 provide graphical representations of "occupational" and "general public" reference level values for exposure durations ≥ 6 minutes. ICNIRP (2020) [60] addresses this issue using the quantity 'power density'. Figures 7 to 9 indicate the ICNIRP reference levels mentioned in the years 1998, 2010, 2020, also it is important to notify that the metric power density is used for frequencies >10MHz and >30MHz as per guidelines of years 1998 and 2020 respectively.

VIII. CONCLUSION AND FURUTESCOPE

This paper has investigated mainly on the latest and current research work on various adverse health effects in human beings due to continuous and discontinuous, short-term and long-term RF EMFs exposures at mmWave frequency bands. It has mentioned the state-of-art threshold levels for exposures to RF EMFs at mmWave frequency bands. However, there are few exposure scenarios like RF EMFs interfering with electrical equipment (also called EMC), potential harms to volunteer research participants, EMFs due to metallic implants which are part of medical treatment are out of scope to the threshold levels mentioned in this paper. The future scope of this work is to establish guidelines and safety measures at THz frequency bands, also consider the EMC influences in defining threshold values. Currently, the EHS health disorders are greatly increasing day by day in people who use smart phones for a long time in a day. Future continuations of this research work include deriving scientific basis which gives relation between the usage of mmWave communication devices and EHS health disorders in humans.

APPENDIX

A. DEFINITIONS

Absorbed Power Density (APD): The power density over unit area and it is measured in W/m^2.

Class-1 Tissues: It includes tissues in hand, foot, leg, thigh, forearm, upper arm, forearm, epidermal, dermal, muscles, fat, bones, pinna and cornea, anterior chamber and iris of eyes.

Class-2 Tissues: It includes tissues in eye, head, back, abdomen, pelvis, thorax, and excluding those defined in Class-1 tissues.

General public: It refers to population includes individuals or groups of all ages with varying health status. It includes vulnerable groups or individuals such as frail, elderly, pregnant workers, babies and young children.

Torso & Head: It consists of eye, head, abdomen, pinna, back, pelvis, and thorax.

Limbs: It consists of forearm, upper arm, hand, leg, thigh, and foot.

Human Body core temperature: It refers to the temperature deep within human body, like in the abdomen and brain, and it varies as a function of age, sex, work rate, time of day, thermoregulations and environmental conditions.

Non-ionizing

Radiation (NIR): It consists of all EMFs and radiations that do not have enough energy to perform ionization in the body. It has photon energies less than 12eV, frequencies less than 3×10^6GHz and wavelengths above 100nm.

Occupational exposure: All exposure to EMF experienced by individuals as a result of performing their regular or assigned job activities.

Occupational exposed people: It includes adults and individuals who are trained on awareness of harmfulness of EMF exposure and take precautions while performing their regular or assigned job activities under known situations.

Power Density: The power crossing a unit area normal to the direction of wave propagation and it is measured in W/m^2.

Specific energy absorption (SEA): The energy is absorbed by a human body tissues per unit mass and it is measured in J/kg.

Specific energy absorption rate (SAR): Rate at which the energy is absorbed by a human body tissues and it is measured in W/kg.

B. GLOSSARY

AED	absorbed energy density
AGNIR	advisory group on non-ionizing radiation
APD	absorbed power density
BR	basic restriction
BS	base station
CNS	central nervous system
CW	continuous wave
ECEP	environment commission of Estonian parliament
EEG	electroencephalography
EHS	electromagnetic hyper sensitivity
EM	electromagnetic
EMC	electromagnetic compatibility
EMF	electromagnetic field
EMR	electromagnetic radiation
HTB	heterogeneous temperature distribution
IARC	International Agency for Research on Cancer
ICNIRP	international commission on non-ionizing radiation protection
IoT	internet of things
IIoT	industrial IoT
MPE	maximum permissible exposure
MS	mobile station
NIR	non-ionizing radiation
OAHE	operational adverse health effect
SAC	Social Affairs Commission
SAR	specific energy absorption rate
SCENIHR	Scientific Committee on Emerging and Newly Identified Health Risks
SEA	specific energy absorption
SSM	Swedish Radiation Safety Authority
RF	radio frequency
THz	terahertz
VAR	volumetric energy absorption rate
WHO	world health organization

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