

Review Article

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Health issues using 5G frequencies from an engineering perspective: Current review

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Abstract: The possible adverse health effects of electromagnetic field (EMF) exposure have been in research focus since radio waves were introduced to telecommunication. Broadcast radio systems, satellites, and mobile communication devices use different bands of the radio spectrum, antennas, modulations, and radiated power. The proliferation of cellular networks and mobile phones as user devices have brought transmitting and receiving antennas in the close proximity of the human body and the head. Hundreds of experiments have been conducted to prove and disprove adverse health effects of exposure. Literature reviews of experimental results have also followed the current developments in technology; however, an exhaustive analysis performed on the methodologies has revealed many flaws and problems. This article focuses on the latest results on frequency bands mostly used for 5G below and above 6 GHz in the mmWave band. Current results do not indicate significant health effects and responses below the current safety limits. Nevertheless, further research directions can be identified, especially for mmWave radiation.

Keywords: 5G, health effects, radio frequency, radiation, EMF

1 Introduction

The possible effects of radio frequency (RF) exposure on living organisms have been investigated since the installation of the first radio towers. Human beings are not able to sense and detect the presence of electromagnetic radiation below and above the frequencies of visible light (apart from thermal effects). Other sources of radiation

(e.g., nuclear) having clear adverse health effects paved the way to conflate different kinds of radiation. The difference between ionizing and nonionizing radiation, together with the well-known hazards of nuclear power (threat of nuclear disaster and weapons), is confusing for the public. Numerous test results have been published on this topic, focusing on power, frequency, and dosimetry – all targeting real or imaginary health issues of living organisms. Since mobile communication has become widely available and ubiquitous, these concerns are greater than ever. The technological development (producing a new generation of a mobile network and system at 10–15-year intervals) is much faster than the ability of society's adaptation to it.

The latest development of the fifth-generation mobile networks, called 5G New Radio (5G NR), has been introduced, spreading with anticipated roll-outs within a few years. In the last 2–3 years, many test sites and public networks have been installed, reasonably priced 5G-enabled mobile devices have hit the market, national and international strategies have been formed, and tech companies have attempted to promote the new services. Nevertheless, neither the industry nor the public is convinced of the necessity for the new technology. The lack of information and the possibility of spreading uncontrolled fake or distorted news on social media platforms have led to enormous resistance to the technology, resulting in misunderstanding, demonstrations, the destruction of cell towers, or even associating 5G with the lethality rate of the COVID-19 disease [1]. All these might be no more than suggestive coincidences: correlation does not imply cause. There is a term for the tendency to construct reasons for connections between what are actually unrelated events: apophenia [2]. There seems to be a human need to explain things based on simply observing how two things tend to vary together. An entertaining homepage was also created to present funny correlations supported by statistical evaluations [3].

In recent years, many articles have been published on this issue focusing on 5G. Some of them deal with measurements, regulations (safety limits of radiation), and simulation methods highlighting existing problems and proposing better models, methods, and research

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directions. Also review papers appeared, collecting and citing relevant results from others with the aim of summarizing recent findings. More may be anticipated to come as increasingly more networks and end-user equipment (UE) will be in operation, and as higher frequency bands will open for 5G (and beyond).

This article is a “review of the reviews” supplemented with the latest results from the past years to highlight the most important issues and problems. The basics of radiation and antenna systems are presented in Section 1. Section 2 deals with measures and health limits depending on the frequency band used for communication. A literature overview of current findings of animal and human studies is summarized in Sections 3 and 4, respectively, followed by the emerging critics and analyses of measurement and evaluation methods that generally lead to misinterpretation of the results in Section 5. Finally, a list of possible research directions is proposed in Section 6.

1.1 Radiation

The word “radiation” has a fundamentally negative connotation for the public. However, it is a neutral category of phenomena that can be harmless (neutral), adverse, or even advantageous. First, we have to separate radiations based on their source, such as acoustical (mechanical energy transport), particle-based (nuclear), and electromagnetic (RF, microwave, infrared, and visible light). Most types of radiation are invisible, inaudible, and undetectable in any ways for humans, which makes them appear more dangerous.

We usually categorize RF radiation as either ionizing or nonionizing depending on the energy of the radiated particles. Energy is directly correlated with frequency: the higher the frequency, the greater the energy. If radiation carries more than 10 eV, it is called ionizing because it would be enough to ionize atoms and molecules, break chemical bonds, and affect living cells (e.g., the DNA).

Furthermore, even relatively low frequencies can cause harm if the transmitted power is large. Sunlight is the most common form of radiation having visible and invisible components. It is the basis of life on this planet that almost every life form needs for it to exist. On the other hand, “too much” sunlight can cause pain, burned skin, ultraviolet radiation, or even pose a risk of cancer. As a matter of fact, UV-A and UV-B radiation are the only nonionizing forms proven to be carcinogen. The most important factors in case of RF radiation is frequency (wavelength), radiated power (energy, power density (PD)) and time of exposure.

A 2015 summary of the scientific literature on the European field strength measurements indicated the mean field strengths between 0.08 and 1.8 V/m, with the majority of field strengths below 1 V/m. No exposure levels exceeded the European Council recommendations [4]. The same year, another review was published on the potential biological effects of nonionizing mmWave radiation, discussing the requirements for future 5G mobile communication networks to be safe [5]. 4G systems use frequencies below 6 GHz. New radio operates in two bands: in Frequency Range 1 (sub-6 GHz), ranging from 450 MHz to 7.125 GHz, and in Frequency Range 2 (mmWave band), ranging from 24 to 50 GHz. In a frequency division duplexing (FDD) system, the carrier wave is always present, while in a time division duplexing (TDD) system, transmission is time variant, resulting in the reduction of the instant maximum received power and in an increasing spectral efficiency. The 4G/LTE system can use both, and Wi-Fi and 5G utilize TDD. Although 5G can use FDD as well, TDD is common in very dense deployments with low-power nodes and for frequency bands usually above 10 GHz, as well as in case of multiple-input and multiple-output (MIMO) antennas and beamforming.

1.2 THz communication

Technologies deal with visible and near-infrared light fall within optics and photonics where well-known physical effects occur (e.g., heating by infrared radiation, photoelectric effects). Although visible light is regarded as non-ionizing radiation, ultraviolet light does have carcinogen effects, so it can be viewed as the starting frequency of ionizing RF radiation. The frequency band between radio waves and infrared light from about 0.1 THz up to 10 THz or even 30 THz (wavelengths of 3 mm to 30–10 μ m) is called the “Terahertz gap.” The lack of operating devices left this gap empty for communication purposes. However, research and development focusing on this region can be the basis for future THz communication [7–9]. Research includes the exploration of the physical effects of radiation and devices transmitting and receiving signals that would be the basis for 6G and other kinds of THz communication (submillimeter radiation).

Figures 1 and 2 show the most important regions of the RF spectrum used for communications. This spectrum usually ends at around 300 GHz, where we can use transistors for our electronic devices. Beyond 5G-systems and networks will have more directionality, shorter communication distances, greater system capacity (Tbps), and

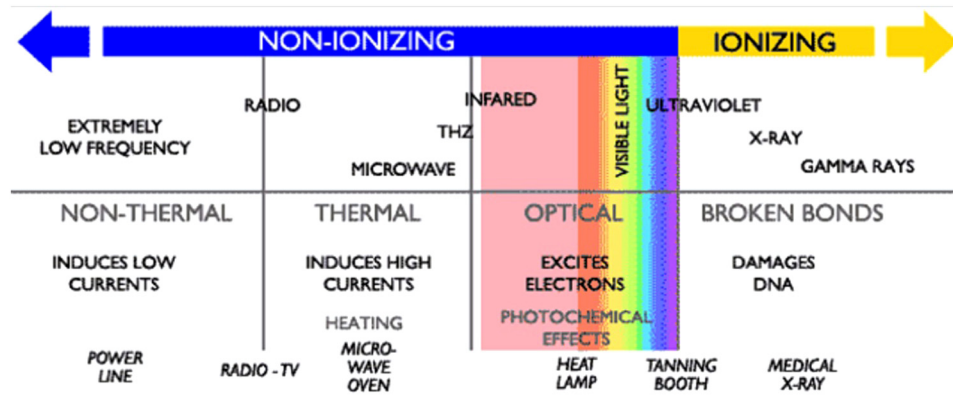


Figure 1: The RF spectrum showing nonionizing and ionizing radiation [6].

user density, mostly for IoT and IoD applications [10–14]. Regarding health issues, it is not clear whether non-thermal effects exist in the nonionizing THz region, and there is no safety limit specified for bands above 100 GHz. In 2019, regulators appeared to be ready to propose a general localized PD exposure limit above 6 GHz of 40 W/m^2 averaged over 1 cm^2 that can be applied up to 3 THz for the general population [15].

1.3 Antennas

Cellular networks usually operate in the microwave domain, often called the “sub-6” band (1–6 GHz). New frequency bands were allocated and opened for future 5G communication above 6 GHz, usually around 25–30 or even up to 60 GHz, called “mmWave” band. As these frequencies are one order of magnitude higher, physical properties (e.g., propagation and diffraction) and health effects can differ from those at lower frequencies. 5G, in particular, will use the lower bands in the mmWave region around 26–28 GHz for specific applications (i.e., industry, transportation). Most of the frequencies allocated for 5G are already in use by other services and use small cells to create higher bandwidth and data rate for special needs. IoT applications will also have

small antennas and transmitting power covering relatively small areas with low data rate. 5G network architectures have been designed with the focus on following main areas: massive machine-type communications to connect large numbers of low data rate IoT devices; enhanced mobile broadband (eMBB) services as an extension for mobile data communication; and ultra-reliable low-latency communication (URLLC) for low-latency applications. The significance of these areas vary, and the current focus is on eMBB services.

Higher frequencies mean shorter wavelengths. The dimension and the size of a transmitting or receiving antenna depend on the wavelength: shorter waves need smaller antennas. On the other hand, propagation is affected: the range (distance) of communication decrease; thus, for 5G, we will need more antennas but smaller than those needed for 4G. Large-sized antennas covering sizeable areas operate with high power to have enough signal strength at the cell borders. User devices such as mobile phones attenuate outgoing (uplink) signal strength in close proximity to the head (the majority of radiation reaching the head and the human body is from the UE, not from the base station). If the density of the network base stations is high, less power is needed both from the base station antennas and from the mobile devices

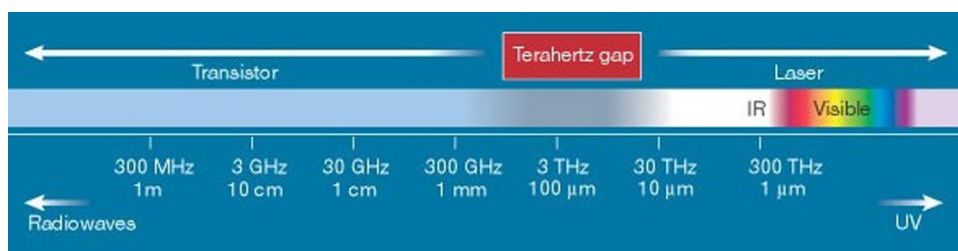


Figure 2: The Terahertz gap [7].

connected to them. Furthermore, the latest generation of base station antennas are not a single piece of equipment, but a (massive) array of elementary antennas with new features, such as beamforming and beam steering, called massive MIMO type antenna.

We can distinguish between the near-field and the far-field of an antenna. If the frequency is low, the boundary can be meters or even kilometers away from the radiating antenna. However, this boundary between the regions is vaguely defined, and it depends on the emitted dominant wavelength (λ) and the size of the radiating element. Near-field is where the distance is shorter than the Fraunhofer distance given by equation (1). Assume d denotes the distance measured from the antenna and D denotes the largest geometrical size of the antenna, the spatial limit (border) of the near-field is when:

$$d < \frac{2(D^2)}{\lambda}, \quad (1)$$

$$3\lambda < d < 10\lambda. \quad (2)$$

In a simplified manner, we can use equation (2). Far-field electric and magnetic field strength decreases as the distance from the source increases (inverse-square law for the radiated power intensity). Near-field strength decreases more rapidly with distance. In the case of 1,900 MHz, the wavelength equals to 0.16 m; at 2,400 MHz, the wavelength equals to 0.125 m; at 6,000 MHz, the wavelength equals to 0.05 m; and at 28 GHz, the wavelength equals to 0.01 m. Regarding mmWaves and microwaves, the far-field of the antenna is used for calculations [16]. Being in the far-field of a base station is easily maintained, but the UE is in the proximity of the head during voice calls and around the border of far-field in browsing mode.

Due to the distance between the users and the antennas in the 5G network, electromagnetic field (EMF) distribution should be calculated in the far-field and the near-field zones with respect to the environment properties, propagation, and predictable radiation pattern of the active antenna system [17]. In former generations, antennas had fixed radiation patterns, and shape and beam direction did not change in time. 5G systems with active antenna arrays can synthesize beams pointing toward different directions, and reconfigure dynamically according to the current network load and number of users. During beamforming, elements in an antenna array can be combined, and at particular angles, this creates constructive interference (high gain pattern toward the UE).

Typical exposure levels in areas accessible for the general public are usually thousands of times below the limit values. An analysis of the peak effective isotropic radiated power (EIRP) levels of UE beamforming arrays

at 28 and 39 GHz showed that in realistic housing integration, the 3GPP requirements on minimum peak EIRP can be generally met under the expected RF EMF exposure restrictions [18]. The transmitted power of a 5G base station is determined by the current traffic load and user behavior. Exposure measured within a specific observation time could be much lower than the theoretical maximum exposure. However, in practice, the complete power is not concentrated on a single beam with the maximum possible antenna gain over a time span. Signals transmitted independently of traffic are in the physical layer of 5G (synchronization signals and the SS/PBCH block). It is usual to obtain the 95th percentile of the transmitted power per beam that would be between 7 and 22% of the theoretical maximum. The 95th percentile exposure can be derived from the maximum theoretical exposure by an agreed-upon reduction factor if a realistic exposure assessment is required. Two extrapolation methods were recently proposed to address this problem [19]. Another study computed a model for time-averaged realistic maximum power levels for 5G base stations using massive MIMO antenna array. The largest level was less than 15% of the corresponding theoretical maximum. Even for very large degrees of system utilization, the maximum was found to take values between 7 and 22% of the theoretical maximum. In the far-field, it allows a reduction of the limit of the so-called compliance distance with a factor of about 2.6. Also, in case of 2G to 4G systems, measurements showed that the actual transmitted power is significantly below the theoretical maximum [17,20].

If the total exposure at a given place is determined by transmitters at different frequencies, a frequency selective measurement method (antennas) is needed to avoid overlapping. Isotropic antennas (i.e., the result does not depend on the direction of arrival and field polarization) up to 6 GHz are available, and selective equipment in the form of spectrum analyzers are usually optimized for the assessment of human exposure. On the other hand, broadband measurements would highlight the effect of contributing transmitters. Probes for field strength measurements are usually isotropic. Amplitude and phase of the electric and magnetic fields are necessary to obtain the PD, but near-field probes for SAR measurement only record the amplitude of the electric field. A PD unit is usually used for mmWaves from 5 cm in the far-field. For shorter distances in the near-field, SAR is suggested to be the better alternative [21]. A current Austrian measurement revealed that both measured and calculated results of electromagnetic radiation, including mobile radio transmitters, DVB-T2, and WLAN base stations, were within

the legal limits. For 5G (at 3.758 GHz), the maximum PD was in the nW/m^2 range. This low PD value can be a result of the current low level spread of 5G services [22]. In Australia, the monitoring of the transmit power for several 5G base stations equipped with massive MIMO antennas and beamforming revealed the maximum time-averaged power per beam direction to be well-below the theoretical maximum and lower than what was predicted by the existing statistical models. Assuming constant peak power transmission in a fixed beam direction led to an unrealistic EMF exposure assessment [23]. Due to the beamforming, the transmitted power is not uniform, it varies over areas and time. However, the appropriate measurement methods and regulations are not yet available. An exposure assessment methodology was also recently proposed, using a spectrum analyzer to measure the instantaneous and theoretical maximum exposure for 3.5 GHz downlink 5G base stations with identification of the synchronization signal block and extrapolation to the theoretical maximum and with the option to adjust the methods in the mmWave domain [24].

2 Measures, metrics, and health limits

The frequency bands allocated for 5G, including both the mmWave and microwave bands, have been used by other RF applications such as microwave communication, satellites, military applications, and radar for decades. Also, research targeting RF exposure goes back many years. On 5G-related frequencies alone, more than 350 studies can be found in the literature, mostly supporting heat stress on tissue as the affecting factor [25]. Organizations such as the FCC, ICNIRP, and the IEEE publish studies and update recommendations, guidelines, and safety limits according to recent findings. The most important measures are specific absorption rate (SAR), incident PD and temperature. SAR is a measure of the rate at which energy is absorbed per unit mass by a human body when exposed to a RF EMF. Safety limits can be set depending on the frequency.

2.1 Health limits

The FCC maximum permissible exposure in terms of PD for frequencies between 1.5 and 100 GHz is 10 mW/cm^2 over a 30-min period. For exposures, a quantity of local tissue SAR of 1.6 W/kg , as determined in any 1 g of body

tissue, is specified. Also, an average value of 0.08 W/kg in any 1 g of body tissue was set for whole-body exposures. A whole-body average SAR of 0.4 W/kg was chosen as the restriction to provide protection for occupational exposure. As extremities (ear, hands, wrists, and feet), the peak spatial-average SAR limit for general population exposure is set at 4 W/kg , averaged over any 10 g of tissue. The localized SAR limits applicable for UE are to be averaged over a mass of 1 g (FCC) or 10 g (ICNIRP and IEEE) of body tissue. The PD limits are considered for an averaging area of 20 cm^2 . SAR provides a better correlation with temperature elevation for exposure durations between 1 and 2 minutes (short duration) at most frequencies [15].

In the draft ICNIRP guidelines, the transmitted PD (classified as basic restriction) and the incident PD (classified as reference level) are the metrics for local exposure above 6 GHz. In the draft IEEE guidelines, the epithelial PD (classified as dosimetric reference limit) and the incident PD (classified as exposure reference level) are the metrics for local exposure above 6 GHz ($1\text{--}4 \text{ cm}^2$ averaging area) [18]. It is important to check the actual limits as they are constantly updated.

It is frequently suggested that above 6 GHz, RF EMF exposure from the UE should be assessed in terms of incident PD, rather than SAR as below 6 GHz. 6 GHz is defined as the transition frequency because of the smaller penetration depth, and correlation between SAR and the increasing temperature is not as strong as at lower frequencies [18]. However, for a direct comparison of radiation effects and exposure below and above 6 GHz, measures and limits must be adjusted [21,26,27]. Frequencies at 3 GHz (IEEE) and 10 GHz (ICNIRP) are also used as transition frequencies from SAR (averaged over 10 g of tissue) to incident PD averaged over a specific area. Furthermore, short pulse (less than 10 s) exposure may lead to large instantaneous temperature elevation on the skin that had to be considered. Energy deposition could occur quickly in a smaller tissue area or mass, causing intense temperature elevation within a very short exposure time period [15]. Nevertheless, PD over 6 GHz was also reported to be not as useful as SAR or temperature in the assessment of safety, since PD does not display the level of EMF energy that is, in fact, transmitted across the boundary or the amount of energy that is indeed “absorbed” in the body [28].

The exposure is typically assessed considering bare skin. In practice, several exposure scenarios involve the presence of textile interposed between a radiating source and the skin (e.g., browsing when using gloves or making a phone call when wearing a hat). Under these conditions, the textile could act as a matching layer affecting

the power absorption in the tissues. A 2021 study investigated, for the first time, the effect of ageing and the impact of textile on the power deposition in a skin-equivalent model under near-field exposure induced by multi-beam radiating structures at 26 and 60 GHz [16]. The maximum increase of the average absorbed PD with respect to the average value for adults was observed in 70-year-old subjects, while the strongest decrease was measured in 5-year-old children. In the case of clothing, the absorbed PD can increase or decrease depending on the properties and the air gap between textile and skin. When using cotton and wool, the maximum increase of the averaged absorbed PD is about 40% compared to the bare skin. It was demonstrated that, up to 5.6 GHz, the whole-body-average SAR in children can go beyond the exposure limits. However, it remains below these limits for adults. By using child models specified by the ICRP, the SAR increase in children was found to be of the same order of magnitude as the numerical calculation uncertainties. The sweaty upper skin layer was investigated and regarded as a helical antenna that increases the skin's SAR in the 400–600 GHz band [29]. However, another author commented that as the applied high-frequency region is not used by 5G, the results are irrelevant on health effects related to 5G, the SAR is much lower below 50 GHz, and the temperature fluctuations under realistic exposure conditions are very small and biologically insignificant [30]. Temperature elevation of a direct contact area is proposed as another appropriate metric for mmWave exposure, especially if the tissue (eyes) is especially vulnerable to heating [27,31]. Both ocular and skin effects can be detected only at higher exposure levels than used by 5G [32]. The communication performance at 26 GHz can be analyzed with the impact of human blockage as well. Failure in communication can be due to severe attenuation effects because of the presence of a human (or vehicle). Simulation results suggest a need for a +13 dB SNR attenuation for the same QoS in practice [33].

2.2 RF exposure in the 5G bands

The introduction of new technologies in RF communication has always been questioned by the public. Even if the benefits are clear, many people are worried about “more radiation,” higher electromagnetic exposure, and an increasing number of antennas.

Frequencies allocated for 5G networks are not new. They have already been in use for other RF communication.

Now, some of these bands were reallocated for different services, e.g., 5G. The lower microwave 5G band below 6 GHz is already “polluted,” e.g., Wi-Fi routers use the 2.4 GHz band without any thermal effects due to the low PD. Furthermore, the expansion of 5G will also bring along the termination of 3G services. As 3G is less effective with larger antennas and higher transmission power, replacing them with 5G technology would be beneficial. After a while, only 4G and 5G systems will coexist for telecommunication. The 3G band will be not shut down completely as other RF services may be in use. Also, mmWave devices have been in operation for a long time (e.g., body scanners at airports), and effects have been studied and documented [34].

3 Animal studies

Radiation exposure experiments generally use animals. To decrease measurement time and costs, most experiments use simple excitation signals (such as unmodulated carrier waves), short exposure times, and high transmitted power to reach the needed dose. Former experiments could be designed and performed more easily because the national and international regulatory basis on breeding, storing, transporting, and handling of the animals was not so strict. The most popular species among vertebrate animals are small-size rodents: mice and Wistar rats. The main focus of adverse effects is on various types of tumors, DNA breaks, oxidative stress, and fertility issues. Next, some experiments will be outlined that include radiation of frequencies also relevant for 5G systems.

Adult male mice received radiation exposure at a large 44 W/kg dose in a waveguide system (2.45 GHz for 30 min). Decreased sperm count and abnormal sperm morphology were observed [35]. Another study evaluated the possible effects of whole-body EMF exposure at 900 and 1,800 MHz (2 h a day for 3 months). An increase in testosterone level, epididymal sperm motility (forward), and normal sperm morphology of rats were detected [36]. A similar experiment using 2.45 GHz (1 and 7 h a day for two months) for two groups of rats showed a decrease in sperm parameters in a time-dependent pattern [37]. Testing the long-term effects of 2.42 W/kg radiation on the testes of rats at 2.4 GHz (24 h a day for one year) showed effects on some of the reproductive parameters of male rats [38]. However, male fertility studies were also criticized for not being scientifically proven evidence reports [32]. A study focused on the effect of microwave radiation at a dose which generally does not lead to tissue heating. In rat testes, however, it resulted in the accumulation

of heat. Whole body pulse radiation at 2.45 GHz and mean PD of 28 W/m^2 were applied (3 h a day for 3 weeks). Body temperature was not elevated, but the testicular temperature was significantly increased resulting in dilated and congested blood vessels, while the seminiferous epithelium showed degenerative changes [39]. An increasing amount of free radicals affect biological systems causing oxidative stress (damage). It is often seen as one of the most important adverse effects of radiation [40]. The effect of 2.45 GHz radiation on histology and the level of lipid peroxide in rats was demonstrated (2 h a day for 35 days with PD of 0.2 mW/cm^2 and estimated SAR of 0.14 W/kg) [41]. Oxidative brain and liver damage and disturbed development of newborn rats were reported as a consequence of 2.45 GHz radiation with 217 Hz pulses and 0.1 W/kg SAR during pregnancy [42]. Increasing the frequency up to 50 GHz can lead to DNA double-strand breaks (head and tail length, intensity, and tail migration), and it may affect brain cells, if rats were exposed to radiation at a power level of 0.86 microW/cm^2 with a SAR of 0.8 mW/kg (2 h a day for 45 days) [43]. Changing the frequency to 2.45 GHz, PD to 0.34 mW/cm^2 , and the estimated SAR to 0.11 W/kg (2 h a day for 35 days) resulted also in damage to the brain, and it was suggested as a source of possible tumor promotion; however, this was not adequately proven [44]. The source was a microwave oven with 50 Hz modulation frequency (input 1,080 W, output 700 W), which presumably produced too high radiation levels. Membrane bound enzymes, which are associated with cell proliferation and differentiation, were also suggested to be tumor promoters [45]. An often cited experiment from 1996 investigated the effects of 2 h exposure using pulsed and continuous waves at 2.45 GHz [46]. PD of 2 mW/cm^2 with a SAR of 1.2 W/kg caused single- and double-strand DNA breaks in the brain cells of rats for both signal presentations. At this frequency, no significant difference was observed between the effects of the two forms of radiation. 2.45 GHz induced oxidative damage, and the protective effect of garlic on rats was shown at low level EMF. DNA damage in both brain tissues and plasma of the rats was observed, and it was also argued that the use of garlic decreases these effects [47]. A review study from 2009 collected evidence from the 100 kHz to 300 GHz band. Animal studies showed no effect of mobile phone type RF exposure on auditory functions. The results of carcinogen studies were rather consistent about effects on rodents that are not likely at a SAR level up to 4 W/kg . Furthermore, results on gene and protein expression were found to be inconclusive, and RF-induced changes found to be very small. Genotoxicity studies also generally indicated a lack of effect. As was expected, heating could be a source of effects on male fertility [48].

Figure 3 shows an overview of animal studies for comparison.

Behavioral studies attempted to examine performance of rats in a maze. Human and animal studies suggest that radiation in the 0.1 MHz to 300 GHz range might interfere with cognitive processes. A former study in 1994 was repeated 10 years later to replicate the decreased performance of rats in a 12-arm radial-maze task. The performance of exposed rats was comparable to that found in sham-exposed or in naive rats. The authors suggested that the microwave-induced behavioral alterations measured by the former authors might have had more to do with factors liable to performance bias than with spatial working memory *per se* [49]. This is also a good example why independently repeated measurements are important to draw conclusions from. The hippocampus is involved in learning and emotional states. The negative impact on the subject's mood and the ability to learn were investigated in rats. Learning and memory, emotional states, and corticosterone levels were measured after RF exposure. No significant differences were observed in the spatial memory test and in morphological assessment of the brain. In some exposed animals, however, there were decreased locomotor activity, increased grooming, and a tendency of increased corticosterone levels [50].

Insects such as *Drosophila* have lately been investigated. Here, 3.5 GHz radiation environments were simulated at intensities of 0.1, 1, and 10 W/m^2 , respectively. The activity of flies was measured using a *Drosophila* activity monitoring system under short-term and long-term exposure. Short-term RF exposure increased the activity level and reduced the sleep duration, while long-term RF exposure reduced the activity level and increased the sleep duration of flies (improved sleep quality) [51].

All the aforementioned experiments were distinct in exposure time, radiation level, and evaluation methods. Only one of them was independently repeated, and it delivered a rebuttal of the original experimental results. A majority of experiments with rats have an insufficient duration of experiment (far shorter than years) and/or too small number of animals to derive statistically significant conclusions [32].

Due to the physiological differences between rats and human beings, extrapolating results of small animals to humans may be inappropriate. Radiation could penetrate much deeper into a small animal's interior [52]. We can speculate that if there is an effect on a rat, transferring the conclusions on human biological effects is not necessarily proven. On the other hand, if there is no response in rats, it is likely that there will be no response in humans.

animal	dose (PD or SAR)	frequency (GHz)	exposure	remark
mice	44 W/kg	2.45	30 min	waveguide system [33]
rats	1.2–3 mW/kg (0.9 GHz) 0.011–0.053 mW/kg (1.8 GHz)	0.9 and 1.8	2 hrs/day; 3 months	whole body exposure [34]
rats	N.A.	2.45	1 and 7 hrs/day; 2 months	whole body exposure [35]
rats	2.42 W/kg	2.4	24 hrs/day; 1 year	[36]
rats	28 W/m ²	2.45	3 hrs/day; 3 weeks	pulsed signal for body heat elevation [37]
rats	0.2 mW/cm ² 0.14 W/kg	2.45	2 hrs/day; 35 days	[39]
rats	0.1 W/kg	2.45	1 h/day; 5 days/week for 3 weeks	217 Hz pulsed [40]
rats	0.86 μ W/cm ² 0.8 mW/kg	50	2 hrs/day; 45 days	[41]
rats	0.34 mW/cm ² 0.11 W/kg	2.45	2 hrs/day; 35 days	[42]
rats	2 mW/cm ² 1.2 W/kg	2.45	2 hrs	pulsed and continuous [44]

Figure 3: Animal studies overview.

5G base stations can have a maximum power range around 100–200 W, far below the limit that could thermally affect a bird flying by, even if absorption of flora and fauna is large at the aforementioned frequencies. Radiation intensity is below 25% of the maximum in 95% of the time. Smaller radiating cells are in the 10 W region. The UE can have an uplink power of 1 W, depending on the actual network status and data rate, and it is always set to the lowest minimum required for the communication (usually around mW). Increased base station power would result in the improved quality of service and decreased uplink power that is beneficial for the user [53]. To extrapolate and to obtain a correct estimation of the instant maximum power received from a 5G source, the effects of beam steering and TDD have to be considered (using a beamforming factor) [54].

4 Human studies

Human studies include the investigations of biological tissue. This can involve removed tissue samples or cells, along with a variety of simulations and numerical methods on

human body and tissue models being applied. Furthermore, psychological and behavioral observations can generally be collected based on self-reporting user habits. Contrasting these reports (questionnaires) with medical documentation can reveal even long-term effects, although results are often inaccurate and inconclusive. Next, some relevant experiments will be summarized on 5G-related frequencies, both low band and high band.

In an Ericsson study, the mechanisms of RF energy absorption by body tissue near wireless equipment were studied, using numerical simulations at frequencies of above 24 GHz. If a realistic body to source distance is maintained (larger than 5 mm), the effect from the reactive near-field on the energy absorption in the tissue is small, and the interaction between the body and the source is modest. Effects of the near-field body interactions were shown to be small when EMF compliance at mmWave frequencies was evaluated. A distance of less than 5 mm can be used for compliance assessments of body-worn devices in case of SAR. In devices that are used close to the ear, antennas are installed on the opposite side of the screen. Thus, antenna distance corresponds to the device thickness, even if it is touching

the face. The reactive near field is expected not to be dominant for distances greater than 2 mm at 24 GHz. In the mmWave bands up to 100 GHz, the free-space EMF of the antenna can be used to characterize the energy absorption in the skin, also for devices used in close proximity to the body. Due to the wide safety margins included in the safety exposure limits, the effects of near-field body interactions are negligible when evaluating compliance in the mmWave band [55].

Temperature elevation in a multi-layer model of the human head and its correlation with PD metrics using a 28 GHz beam steering patch antenna, a dipole, and plane wave were investigated. The PD averaged over 1 cm², and the peak temperature elevation in tissue at 28 GHz induced by plane waves had a good correlation. An average area of a few square-centimeters is suited for spatial-averaging the PD [56]. Of particular concern are the effects on the developing brain in children, where radiation can penetrate deeper into the brain, creating greater doses per unit volume. Furthermore, tissue behind the thin skull bone could absorb a 10-fold higher local dose [57]. The numerical methods of human models for the estimation of the absorption of RF energy from a 28 GHz antenna revealed that common exposure scenarios comply with the safety limits; however, local SAR level and distribution showed differences between adults and children [58]. Based on a three-layer head model simulation, a 27–30 GHz antenna array was designed to achieve low SAR values in the mmWave domain. If the radiation pattern of the antenna is directed to the top or bottom edges of the device, the influence of the user's hand on the antenna radiation is minimized. The effect of the hand is critical for the UE. Radiation penetration and SAR in the brain decrease with the increasing frequency and depth. For mmWaves, absorption rapidly decreases with depth, and it does not reach deeper tissues (more than about 2 mm). The skin of the palm can be as thick as 2 mm, and an electrically large object makes simulations time and cost expensive. In mmWave frequencies, power absorption and body blocking effects are important when the user holds the UE but does not directly block the antenna, and the absorption is lower than it would be at below 6 GHz [21,59]. Body blocking can reach 30 dB, and hand blocking can be around 2–4 dB depending on the way of holding a device. A numerical dosimetry study for a 60 GHz antenna showed power absorption increment in the head even in the presence of the hand. The body also influences the antenna performance (e.g., radiation pattern, efficiency) depending on how the user holds the equipment (call scenario and browser scenario). Thus, maximum absorption is on the ear and fingertips. Both ears and hands are in the near-field

region of the antenna. The antenna is best placed on the edge of the UE with a maximum power around 85 mW [60].

There are also differences in tissue properties: numerical calculations showed that the SAR and temperature rise distributions are different; they are lower for healthy brain tissue than for a brain tumor in the head [61]. Effect on different tissues is also due to the dipolar property of biological tissues, causing increased polarization effects based on the different dielectric properties [62]. Besides real brain tissue, brain simulating gel can also be used for tests. By using three frequencies at 1.9, 4, and 39 GHz, results revealed that both temperature change and SAR are applicable metrics below and above 6 GHz. RF heating increases rapidly with frequency due to the decreasing RF source wavelength and the increasing PD with the same incident power and exposure time. The study did not consider the layers of skin, fat, muscle, and skull containing the brain in a realistic head model. The actual PD and the heat diffusion reaching the surface of the brain in a real head will obviously not be the same as the values showed in this study [63]. Dominant factors influencing power absorption in terms of whole-body average SAR based on modeling can be computed. Results showed that absorption peak in the resonance frequency region greatly depended on the electric properties of tissue, while the peak in the GHz region is affected mainly by the surface area [64,65].

Physical properties of the electromagnetic wave determine the depth they can enter another physical object. Part of the energy will be reflected; another part will be absorbed. In the case of 5G, frequencies in the mmWave range will penetrate some millimeter deep in the skin, if the naked skin is assumed. It is influenced by the fact whether the skin has hair, is wet, or is covered with clothing. They do not reach the bones or inner organs. Effects are generally thermal (heating) effects, and special attention is given to the eyes, the outer ear (earlobes), palm, and fingertips. Wireless devices operating above 10 GHz may transmit data in (pulsed) bursts of a few milliseconds to seconds. Time- and spatial-averaged PD values can be lower than the limits for continuous exposure, and the bursts may lead to short-temperature spikes (tens of degrees) and oscillations in the skin of exposed people [66]. At 30 GHz, the penetration in the ear canal and in the tympanic membrane did not cause thermal effects [21].

RF radiation can cause cell damage in case of ionizing radiation. Current frequencies used for telecommunication services are below this frequency limit. However, thermal effects occur at microwave frequencies, where water molecules can be excited leading to increased temperature around or in the tissue. Microwave ovens generate high power (200–1,000 W) 2.45 GHz radiation creating

enormous heating effect of material with high water content. Microwave ovens are, therefore, shielded and have the doors closed during operation so that no radiation escapes. Note that Wi-Fi routers use almost the same frequency (2.4 or sometimes 5 GHz) but with a power of 30–500 mW, usually around 100 mW. We would need several thousand routers concurrently to experience some heating effects.

4.1 On possible adverse health effects

In 2011, the WHO IARC classified RF-EMF as “possible carcinogenic to humans.” In the same category (Group 2B) fall another 321 materials and events, including aloe vera, some Asian vegetables, and the work conditions of firemen [67,68]. Even for carcinogens at the maximum level (level 1), the dose plays a crucial role in determining the carcinogenicity of a substance or exposure. For example, a low dose of a carcinogen may have no impact on health.

In 1998, a review article already started to look at the effects of mmWave. Earlier studies reported on obvious thermal effects, but also showed nonthermal effects at low intensities. Negative and positive responses were reported depending on the frequency, power, resonance, and exposure time [69]. In 2018, review articles were published with the same focus. However, they were updated to the current status: concerns about the introduction of 5G systems, highlighting research articles about various experiments using RF bands of former generations of mobile networks and even earlier [28,40,52,70–76]. These reviews mainly emphasize existing responses, citing long lists of experiments and scenarios, using terms as “delivering strong evidence,” “building a body of evidence,” “supported by massive literature,” and “high level of scientific certainty” regarding brain cancers, glioma, acoustic neuroma, reproductive, metabolic and neurologic effects, DNA damage, neurocognitive disorders, sleep disturbance, oxidative stress, and dozens more. The Bioinitiative homepage has been preparing reports since 2012, where readers can find all kinds of studies regarding its scope [77]. A book containing 8 chapters on the biological harm of 5G and other RF radiation, and pathophysiological effects caused by nonthermal microwave radiation was prepared for the 5G Summit. It declares pulsed EMF biologically more active than continuous waves [78]. The risk of a tumor generally increases with the intensity of the radiation and the accumulation of the exposures [79]. Outcomes often suggest that 5G technologies are far less studied for

human or environmental effects, and experiments often try to transfer results obtained from 2G–4G systems. Existing methodologies for EMF measurements in 2G, 3G, and 4G networks are not suitable for 5G, because they lead to a systematic overestimation of the results when applied to 5G networks [17]. Major concerns in case of 5G are the following: an increasing number of antennas, an additional increase in overall EMF exposure, possible physical and mental impacts, magnification of effects by synergistic adverse exposures, existing nonthermal effects of nonionizing radiation, industrial and governmental bias toward neglecting effects, and underestimating risks. These articles may confuse readers, who will wonder how humanity is not yet extinct.

Regarding frequency bands related to 5G, both low-band and high-band radiation were examined. Neurological changes and discomfort, tissue damage, brain cell damage, metabolic disturbances, and sleep disorders were indicated in the existence of EMF radiation, by both cell towers and UE, mostly below 3.6 GHz [80]. Above 6 GHz, the uplink is usually reported if a transmitter is close to the human body. Simulation results suggest that the downlink of 5G can generate higher PD and SAR than the previous generations of wireless systems [28]. It is important to limit the maximum output power for the UE, although this factor has a direct impact on the system capacity and coverage. Current limits and regulation must be evaluated and updated for devices operating in the mmWave frequency range [26]. The results, however, differ significantly based on the assumptions. If measurements and simulations do not represent realistic scenarios, they overestimate the effects. In this article, a protocol is proposed to decrease the exposure level at a slight cost of downlink performance degradation, although guaranteeing the data rate within the 5G requirements. Beamforming also contributes to EMF that is basically different for 5G than for other previous systems; thus, proper time and spatial averaging methods are needed to avoid false interpretations. An update of current safety limits and regulations is also often proposed based on experimental results and to even postpone and suspend 5G roll-out based on the precautionary principle. Nevertheless, the effects of mmWave radiation are an under-researched area. Early studies on mmWaves demonstrated effects of low-intensity radiation (10 mW/cm² and less) on cell growth and proliferation, enzymes, cell genetics, and other biological systems. Local exposure can even stimulate tissue repair and regeneration, and it could facilitate recovery in a wide range of diseases. It was also argued that they have a nonthermal effect because living organisms could not have developed adaptation to mmWave radiation during evolution [69]. There are other mmWaves studies showing

beneficial effects as well, depending on frequency, modulation, PD, polarization, and exposure time – a therapeutic method used in medicine [40]. Therapeutic applications of low-intensity mmWaves (15–60 mins for 8–15 days) include treatments of surface lesions, repair of deep tissues, and the treatment of cancer – seldom causing adverse or allergic effects [69].

Electro-sensitivity or hypersensitivity was also mentioned by authors as a phenomenon to be recognized as a “well-defined clinical-biological entity” [40,70]. This, however, was challenged by controlled double-blind experiments, where none of the symptoms could be related to this phenomenon. There is no causal relationship between short-term exposure to EMFs and the subjective well-being in members of the public whether they report perceived sensitivity to EMFs [32,81,82].

Recently, a problem occurred regarding American diplomats serving in Cuba, as they experienced various psychological and auditory effects, dizziness, vertigo, and confusion. It was termed the “Havana syndrome,” and it was related to some kind of potential RF exposure, mainly microwave based. These explanations (microwave weapon) were highly speculative, unsupported, and up to date, not confirmed [83–88].

Standardization activities and scientific studies related to the assessment of human exposure to EMFs are constantly reviewed, summarizing the differences of human exposure standards and assessment of consumer products and medical applications [31,65].

5 Criticism in the literature

Invalid conclusions, misinterpretation of results, or false argumentation might not be recognized by readers even if researchers had the best intentions. Preconceived ideas, a conflict of interests, or a compulsion for conformity may also enhance this phenomenon. Only a few studies, mentioned earlier, fulfill the minimal quality criteria to allow for any further conclusions. In fact, almost all RF laboratory experiments that have been performed to date are flawed/limited with respect to showing the full (adverse) impact of wireless radiation that would be expected under real-life conditions. Although it is suggested that RF radiation may be different in the case of synergistic adverse effects, experiments should focus on the radiation itself instead of other “toxic” chemical and biological environmental issues [52,72,89].

To illustrate how this works, let me present the following simplified example. One would like to prove that Wi-Fi is harmful for human users and has adverse effects

on tissue. To do so, he puts some animal tissue, e.g., chicken liver into the microwave oven that operates at the same frequency. To reduce measurement time and cost, the maximum power level is set on the oven. In less than 2 minutes, the sample explodes, as expected. Consequently, the use of Wi-Fi could cause serious health problems; thus, based on the precautionary principle, it had to be banned until the opposite is proven. This is a good and realistic example of a sloppy measurement design, incorrect data acquisition, and evaluation followed by wrong conclusions and lack of independent replicability. Presented in scientific language, by using mathematical expressions and authority of the author, it could result in fraudulent and unsupported “evidence,” or even fake news. As a matter of fact, a similar measurement was installed and published [44].

A recent review was published on the effects of RF radiation (including 5G below 30 GHz) based on 94 publications. Although 80% of the *in vivo* and 58% of *in vitro* studies showed responses to exposure, there was no consistent relationship among PD, exposure duration or frequency, and exposure effects. The studies did not provide adequate and sufficient information for a meaningful safety assessment, or for the question about nonthermal effects. Many experiments were unsatisfactory, using medical devices instead of real 5G equipment, and half of them used PD values tenfold of the safety values (with no indication that higher PD results in more frequent responses). Although the majority of mmWave studies showed effects, no in-depth conclusions could be drawn regarding the biological and health effects in the 6–100 GHz band because too few studies fulfilled the minimal quality criteria to draw conclusions [72].

One of the most cited long-term evaluations is the Danish cohort study and its update from 2011 [90]. On the basis of a large nationwide cohort study of more than 350,000 mobile phone subscribers, the authors concluded that there were no increased risks of tumors of the central nervous system, providing little evidence for a causal association. In the case of people who had used mobile phones for 10 years or more, higher risks of cancer were not associated with long-term use. There was no increased risk in temporal glioma. A small to moderate increase in risk for subgroups of heavy users (for longer periods than 10–15 years) could not be ruled out.

Another population-based cohort study of women aged between 50 and 64 years was created in the United Kingdom to find a correlation between breast cancer and environmental effects [91,92]. The 1999 study was extended with brain tumors and the use of cellphones. During 14

years of follow-up of 776,156 women who completed the 2001 questionnaire, a total of 3,268 incident brain tumors were registered. Compared with users without cellphones, no statistically significant associations were found, overall or by tumor subtype. It has to be mentioned that only middle-aged women were questioned with a relatively low telephone usage per week. An interview-based case-control study from 2010 with 2,708 glioma and 2,409 meningioma cases and matched controls was conducted in 13 countries using a common protocol for the same reason [93]. Overall, no increase in the risk of brain tumors was observed with the use of mobile phones. An increased risk of glioma was hypothesized at the highest exposure levels, but biases and error prevented a causal interpretation.

A review of 5G risk analysis indicated no scientific evidence supporting any of the health issues, while also highlighting the need for further investigation. In 2020, according to an IEEE statement, mmWaves do not penetrate the inner tissues of organisms, overall RF exposure levels due to 5G is not altered, and it is mostly influenced by the uplink radiation of the UE and stay below the current safety limits [53,89]. Research data do not support adverse health effects as long as radiation is below the current limits and within the guidelines. There is no evidence for nonthermal effects of radiation across the whole RF spectrum at levels below the limits. The effects of sufficiently high level of exposure that may cause a reaction of skin heating need to be compared with the effects initiated by infrared heating.

In 2021, a review of 107 experimental studies concluded that biological effects of radiation above 6 GHz remaining below the limits were inconclusive, due to methodological limitations. Measurements were not independently replicated and validated, and they were insufficiently designed and performed with inadequate dosimetry and temperature control. Epidemiological studies showed little evidence of health effects including cancer, DNA damage reproduction system, and other diseases in well-designed studies. It showed no evidence that low-level RF fields above 6 GHz are hazardous to human health [94].

Another 2021 study reviewed and analyzed the current state of knowledge about 5G-related radiation effects in a 50-page article citing 280 relevant sources [32]. Analysis was focused on MIMO antennas and beamforming, densification of base stations, the use of mmWaves, and the multiple connection of a large number of devices. The results suggest no evidence for health concerns from the communication engineering perspective if radiation is below the limits. Many former studies used irrelevant test conditions and are far too conservative in contrast to real scenarios. Of many animal studies, only two

experiments fulfilled the conditions for conclusive evaluation, finding a statistically significant increase of heart Schwannomas by male rats exposed to the highest EMF level (2G system without mmWave exposure). Population-based human studies (tens of thousands of users, more than a decade of observation) did not show any link between the use of mobile devices and the risk of tumors. Patients with cancer were involved in studies, which inquired about their mobile phone using habits. Based on the different use of modulation, signal strength control, and area coverage, 5G systems are not directly comparable to former systems; thus, different statistical and averaging methods are needed. The overall exposure must be measured in the case of coexisting technologies. Therefore, if the limit is reached or the site is nearly saturated, new installments are overlooked. Classic radio and TV broadcast towers have much larger exposure levels than cell towers for mobile communication. Some mitigation techniques are also discussed for future developments in terms of device, network, architectural, and regulatory bases.

5.1 Biased results

A recurring criticism of research and publications is the bias effect. Vendors, manufacturers, service providers, as well as governments and policy makers (such as the ICNIRP) seem to be influenced and biased toward the results of their interests [40,52,95,96]. On the other hand, the media, yellow journalism, fake news portals, and uncontrolled social media presence usually present only results that suggest effects. A Croatian case study investigated whether a news website manipulates information on the health effects of 5G. They concluded that the misinformation is produced within the website, such as erroneous referencing, and the denial of the existence of scientific literature on the topic [97]. The risk perception of humans is strongly individual over large population samples, which is also present in case of 5G. It was found that interindividual differences in risk perceptions were strongly associated with hazard-related and person-specific drivers, and they correlate with people's policy-related attitudes [98].

5.2 Densification

In case of 5G and mmWave applications, a dense network of base stations is needed. Because the wavelength is

shorter, the path loss increases, and consequently, antennas have to be placed in closer proximity. This is called densification. A natural concern arises, whether more antennas result in an increased overall RF exposure and pollution.

Recently, many articles published falsely claimed densification as the main factor for increased EMF pollution [57,73,99]. Using a simple model and a closed-form expression, evaluating RF pollution at different distances between user and the 5G base stations, it was shown that a dense 5G deployment is beneficial to the users living in the proximity of the base stations, with an abrupt decrease of exposure (up to three orders of magnitude) compared to a sparse deployment [100–103]. RF exposure decreases in intensity when the number of 5G base stations is increased. The contribution from neighboring stations does not impact the results significantly. When the UE minimum sensitivity threshold is increased, there may be a slight increase in RF pollution.

During 5G network planning, it must be considered that base stations are not constructed as a single antenna, but use arrays of smaller radiators to establish beam-forming possibilities and also higher path loss. The overall exposure will be low, although short-term radiation peaks may occur if small cells are densely installed. Shared equipment by service providers in urban areas would also result in decreased exposure [104]. 5G will not result in a large proliferation of new base stations, because most base station areas are already saturated in urban areas. With the increasing number of base stations, the exposure will be more uniform over the area. Regulations limiting the installation of 4G base stations had a negative impact on the exposure levels of the UE (increasing uplink power and the possibility of being served by a base station far away) and on the performance quality.

6 Experiment design and future perspectives

In general, journals are biased toward publishing positive results and toward findings that reveal some kind of new discovery. These are usually supported by classic statistical claims using, e.g., the p -value, often misinterpreted its meaning [105]. A highly cited article in medicine revealed that most of the published research findings are in fact false, and the limit of being “statistically significant” should be changed from $p < 0.05$ to $p < 0.005$ [106,107]. Type I error probability (false positive) corresponds to the significance

level. Lowering the p -value would result in less false positive outcomes of experiments.

Whether a study can be reproduced is a key question, especially if great discoveries are reported. A series of repeated psychological studies revealed that 97% of reported significant results could be justified only by 36% in repeated experiments as significant [108]. On the other hand, “statistically not significant” does not mean “no effect” at all.

Both exploratory and confirmatory studies use, i.e., the p -values, but they should be different in design and statistical evaluation. There is a vast literature about Questionable Research Practices (QPR), i.e., HARKing (inventing the Hypotheses After the Results are Known), p -hacking (activities to create statistically significant outcomes), and similar practices [109–114]. The most important problem is selective reporting, where only the favored results and statistically significant findings are reported. This is scientific misconduct even if it is unintentional. All these practices are very common in every field of research, and the field of RF induced health effects is no exception.

The current review analysis of prior experiments highlighted the methodological and experimental flaws, biased results, misinterpretation of measured data, and the inappropriate evaluation and statistical methods in both animal and human studies. Animal studies include a low number of individuals, short-term exposure times with unrealistic radiated power, and using simple signal generators without 5G compatible signals. Considering the costs of the proper measurement systems capable of realistic 5G scenarios in the mmWave range, it is highly unlikely that the setups were designed appropriately. Furthermore, previous results obtained with 2G–4G systems are not transferable to 5G systems.

Summarizing the future directions and parameters of research, designing, and evaluating experiments, the following should be considered:

- (1) realistic scenarios must be designed that are very similar or identical to those used by 5G, including frequency bands, beamforming, and beam steering methods and realistic power densities below the current safety regulations (dosimetry);
- (2) applying real or simulated 5G signals with carrier waves, orthogonal frequency-division multiplexing modulation, TDD methods, and signaling;
- (3) long-term exposure should be guaranteed similar to real-life conditions (i.e., 2 years or more);
- (4) increased number of animal subjects should be included and divided into control and exposure group(s), evaluated double-blindly;
- (5) in case of behavioral studies, animal control groups should go through the same procedure of

maintenance and transportation as exposed groups to detect stress effects independent of radiation (e.g., applying the exact same procedures but using fake antennas without the measurement equipment);

- (6) animal studies must be extended beyond rats and mice, including insects and mollusks having thinner skin and deeper penetration – especially in case of mmWaves;
- (7) in case of mmWave radiation, accurate temperature control and measurement of the exposed tissue should be maintained (instead of measuring only the temperature of the surrounding environment), separating constant and pulsed radiation-induced temperature elevations, and/or infrared heating effects of control groups (if applicable);
- (8) human studies must be initiated in collaboration with service providers and subscribers (utilizing network traffic data, automated logging of user habits with pre-installed applications) extended and compared by medical patient data;
- (9) base station radiation (downlink) must be distinguished from UE radiation (uplink), because the latter is far more important for the user, and above 6 GHz, the near-field exposure of UE should also be considered;
- (10) carefully designed measurement and evaluation procedures should be executed parallel, or independently replicated;
- (11) bias of results should be avoided by excluding “pro” and “against” preconceptions, and thereby warranting independence;
- (12) proper statistical methods must be applied for evaluation, especially for averaging over time and area to avoid unrealistic overestimation of exposure;
- (13) multidisciplinary researchers should be involved, including experienced RF engineers for designing setup and installing equipment, vets and medical doctors for the biological evaluation of tissue, blood samples, and behavior.

It should be emphasized that the aforementioned criteria are difficult to be met, especially the handling of rodents over a longer time period, according to the local national regulations. Breeding, transportation, catering, handling during intervention, as well as collecting and storing samples of large number of animals require qualified personnel and 24/7 supervision over an extended period of time.

Furthermore, enormous costs can appear in purchasing equipment for the mmWave region. A current tender in 2022 has included a proper signal generator capable of producing 5G signals, a 10 W 40 GHz wide-

band amplifier, one antenna, and two cables, all of which have exceeded 300.000 EUR of funding. Although automated measurements can be programmed, constant supervision is needed by the technical personnel.

The most difficult part would be the criteria for the independently replicable measurements. If experiments are executed parallel, the costs will double. If an experiment were to be repeated subsequently, some of the costs could be reduced (first, the measurement equipment), but the time spent for the experiment will double.

International cooperation among various research institutions and universities are recommended, and in the case of determining human user habits based on network traffic data, the involvement of local service providers is also necessary.

7 Conclusion

This article provided an overview of the latest results of research on the health effects of RF radiation, used by 5G in the lower band (sub-6 GHz) and higher band (mmWave). Although many experiments were conducted and reported in the literature showing possible adverse health effects, most of them were inconclusive, poorly designed, and failed to meet the basic criteria of correct scientific evaluation. Conversely, papers presenting no health effects are seldom published and cited by review articles. A strong bias can be found towards publications about putative effects. There is, however, no supporting evidence that exposure generated by radio base stations under realistic conditions have adverse health effects. Based on a thorough analysis of the reviews and focusing on the special properties of 5G communication, a list of criteria has been proposed to direct further research in this area.

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