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Review Paper

IEEE Committee on Man and Radiation—COMAR Technical Information Statement: Health and Safety Issues Concerning Exposure of the General Public to Electromagnetic Energy from 5G Wireless Communications Networks

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***Abstract*—This COMAR Technical Information Statement (TIS) addresses health and safety issues concerning exposure of the general public to radiofrequency (RF) fields from 5G wireless communications networks, the expansion of which started on a large scale in 2018 to 2019. 5G technology can transmit much greater amounts of data at much higher speeds for a vastly expanded array of applications compared with preceding 2-4G systems; this is due, in part, to using the greater bandwidth available at much higher frequencies than those used by most existing networks. Although the 5G engineering standard may be deployed for operating networks currently using frequencies extending from 100s to 1,000s of MHz, it can also operate in the 10s of GHz where the wavelengths are 10 mm or less, the so-called millimeter wave (MMW) band. Until now, such fields were found in a limited number of applications (e.g., airport scanners, automotive collision avoidance systems, perimeter surveillance radar), but the rapid expansion of 5G will produce a more ubiquitous presence of MMW in the environment. While some 5G signals will originate from small antennas placed on existing base stations, most will be deployed with some key differences relative to typical transmissions from 2-4G base stations. Because MMW do not penetrate foliage and building materials as well as signals at lower frequencies, the networks will require "densification," the installation of many lower power transmitters (often called "small cells" located mainly on buildings and utility poles) to provide for effective indoor coverage. Also, "beamforming" antennas on some 5G systems will transmit one or more signals directed to individual users as they move about, thus limiting exposures to non-users. In this paper, COMAR notes the following perspectives to address concerns expressed about possible health effects of RF field exposure from 5G technology. First, unlike lower frequency fields, MMW do not penetrate beyond the outer skin layers and thus do not expose inner tissues to MMW. Second, current research indicates that overall levels of exposure to RF are unlikely to be significantly altered by 5G, and exposure will continue to originate mostly from the "uplink" signals from one's own device (as they do now). Third, exposure levels in publicly accessible spaces will remain well below exposure limits established by international guideline and standard setting organizations, including ICNIRP and IEEE. Finally, so long as exposures remain below established guidelines, the research results to date do not support a determination that adverse health effects are associated with RF exposures, including those from 5G systems. While it is acknowledged that the scientific literature on MMW biological effect research is more limited than that for lower frequencies, we also note that it is of mixed quality and stress that future research should use appropriate precautions to enhance validity. The authorship of this paper includes a physician/biologist, epidemiologist, engineers, and physical scientists working voluntarily and collaboratively on a consensus basis.**

Health Phys. 119(2):236–246; 2020

Key words: microwaves; radiation, low-level; radiation, non-ionizing; safety standards

INTRODUCTION

FIFTH GENERATION, or 5G, refers to a set of engineering standards[2] for operating mobile wireless networks. It handles

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All of the authors named on this TIS as well as many of the members of COMAR have, at one time or another, been retained as a consulting expert in their field by one or more of the following entities: International and National Governmental Departments, Organizations and Agencies; State and Local Governmental Authorities; Public and Private Universities; Members of the Public; Public and Private Non-profit Organizations and Public and Private For-profit Corporations. These include entities with interest in the biological effects of non-ionizing radiation. The data presented and discussions included in this manuscript represent the collective judgment of COMAR who contribute their time voluntarily. No drafts of this manuscript were reviewed by or influenced by any of the aforementioned entities. Furthermore, the views expressed in this TIS are not intended to necessarily represent the views of any other organization including the EMBS and the IEEE.

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(*Manuscript accepted* 18 *April* 2020)

0017-9078/20/0

DOI: 10.1097/HP.0000000000001301

[2] 3GPP. 5G NR (New Radio) is a new radio access technology developed by the Third Generation Partnership Project (3GPP) 3GPP for the 5G mobile network developed as a global standard for the RF portion of the circuit between cellular phones and an active base station in 5G networks.

Table 1. Estimated data traffic during the first quarter of 2014 through 2019 (extracted from Ericsson 2019).

Year (Q1)	Voice (exabytes)	Data (exabytes per month)
2014	0.2	2.3
2015	0.2	3.6
2016	0.2	5.7
2017	0.3	9.7
2018	0.3	15.9
2019	0.3	29.0

data significantly faster than 2G/3G/4G technologies, whose capabilities are approaching their limits and falling short of expected future demands. 5G has significantly greater data transfer rates (bandwidth) and much shorter delays (latency) at the base station in responding to incoming signals. 5G will also be needed to manage the data traffic on present wireless networks, which is increasing by 90% per year. As of early 2019, data traffic stood at about 29 exabytes (29×10^{18} bytes) per month (Table 1). For perspective, one exabyte of data could store 100,000 times the information in all printed material in the U.S. Library of Congress.[3] 5G began its first commercial launches in several countries in Europe, Asia, and North America in 2018–2019, with widespread commercial adoption planned for the early to mid-2020s (Pujol et al. 2019). Fig. 1 depicts the expansion of 5G in the coming years.

In June 2019, a workshop was convened by the Government-University-Industry Research Roundtable (GUIRR) to discuss the cutting-edge issues related to 5G technology and its deployment. According to the workshop proceedings, Nada Golmie of the National Institute of Standards and Technology (NIST), "...indicated that 5G will substantially improve communications capabilities through innovations in connectivity, adaptability, and capacity because the use cases and applications of 5G technologies are wide-reaching and transformational in areas including—but not limited to—agriculture, transportation, and energy." (NAS 2019).

Initial applications of 5G include transmission of multiple streams of high-resolution entertainment content to multiple users simultaneously (e.g., videos and gaming applications) at a capacity large enough to relieve traffic congestion on wireless networks. Real-time 5G communications will enable humans and machines to control or operate remote equipment and devices to accomplish tasks such as remote surgery, repair of equipment in hostile environments, and remote control of aircraft and other vehicles. Other advanced applications might include control of medical devices on the surface of the body or implanted within it (e.g., insulin pumps or cardiac devices) or augmented reality applications on cell phones.

5G wireless networks, and their predecessors (2-4G), are sometimes called "cellular" networks because of the way the network base stations create "cells" of coverage to mobile subscribers. As subscribers move through the cells, the network "hands off" the connection with the subscriber to the next cell. This enables the same frequency bands to be used repeatedly across a large geographic area with minimal interference. As these networks continue to mature, they are often referred to as mobile-wireless or simply wireless networks, which is the term used here.

Technical background

5G is not specific to frequency and will operate across the RF spectrum: a "low band" below 1 GHz for voice and support of many IoT (Internet of Things)[4] applications; a "middle band" in the 1-6 GHz range—already in use and in many cases nearing capacity—in which the 5G protocols will enable faster data transfer compared to 2-4G; and a new "high band" of ~30-300 GHz in the millimeter wave (MMW) portion of the spectrum corresponding to wavelengths from 10 mm to 1 mm that can support extremely high data transfer rates. MMWs are not entirely novel to the environment, as they are found in applications such as airport scanners, automotive collision avoidance systems, and perimeter surveillance radar security systems. The specific band used for 5G will vary by country; for example, in several nations in Europe, 5G was principally introduced in the 3.6 GHz band.

To provide adequate spectrum for 5G, the US Federal Communications Commission (US FCC) has already auctioned spectrum at 24 and 28 GHz and continues to auction frequencies in the 37 GHz, 39 GHz, and 47 GHz bands, with other countries taking similar measures. While the use of MMW allows transmissions across very large bandwidths at higher frequencies, they are readily absorbed outdoors by flora (e.g., wet trees and their foliage) and by building materials, such that a receiving/transmitting device deployed on the building exterior is necessary to receive and transmit the signal to the intended recipient within. Although 5G will operate across a wide spectrum (see above), discussions among the public concerning health and safety issues focus generally on 5G's MMW transmissions.

Sources of RF exposure from cellular telephone networks. Exposure to RF fields from a cellular network originates from two possible sources: one is the "downlink" signal from the base station, while the other is the "uplink" signal from one's own or a nearby person's handset. Handsets can transmit at power levels of up to about 1 watt, but their actual output is set by the network to the lowest level

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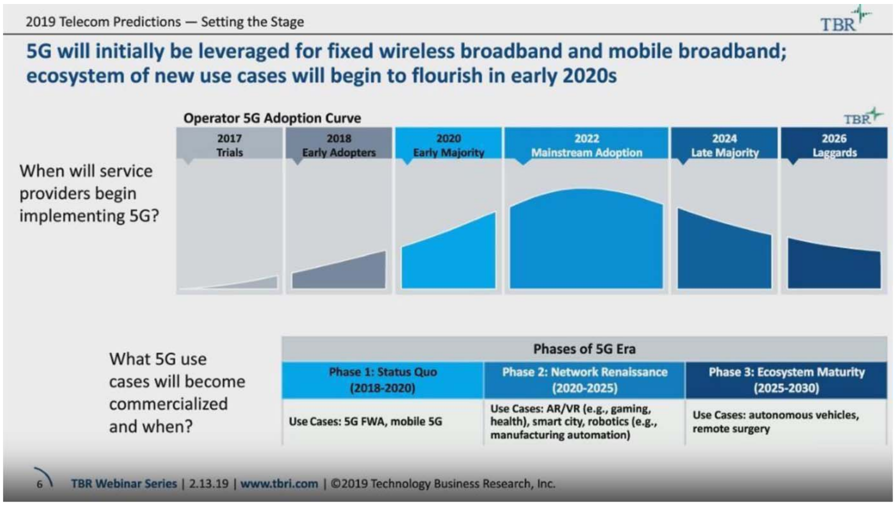
[3] Wikipedia https://en.m.wikipedia.org/wiki/Exabyte. Accessed 6 April 2020.

[4] The Internet of Things represents a network of Internet connected devices capable of collecting and exchanging data without requiring human-to-human or human-to-computer interaction.



2019 Telecom Predictions — Setting the Stage

TBR

5G will initially be leveraged for fixed wireless broadband and mobile broadband; ecosystem of new use cases will begin to flourish in early 2020s

Operator 5G Adoption Curve

When will service providers begin implementing 5G?

2017 Trials	2018 Early Adopters	2020 Early Majority	2022 Mainstream Adoption	2024 Late Majority	2026 Laggards

What 5G use cases will become commercialized and when?

Phases of 5G Era		
Phase 1: Status Quo (2018-2020)	Phase 2: Network Renaissance (2020-2025)	Phase 3: Ecosystem Maturity (2025-2030)
Use Cases: 5G FWA, mobile 5G	Use Cases: AR/VR (e.g., gaming, health), smart city, robotics (e.g., manufacturing automation)	Use Cases: autonomous vehicles, remote surgery

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Fig. 1. 2019 Telecom predictions for 5G adoption within the Industry. Reprinted with permission of Technology Business Research, Inc.

that communicates effectively with the base station, in some cases as low as a few milliwatts.

The power[5] transmitted by a base station varies with the area it serves, ranging from several hundred watts in a "microcell" base station mounted on a tower or on the top of a building, to typically less than 10 W for a "small cell" mounted on a 10-m utility pole, to mW for 'microcells, picocells or femtocells'[6] commonly mounted in the celling or on the inside wall of a building and to serve very limited areas. The signal's frequency depends on the wireless provider and on which of several different services (voice vs. data) the provider supports in a particular region.

When cellular networks were first introduced in the 1990s, there were few subscribers, and cells covered large areas (several km in radius). Their base stations and antennas (macrocells) were mounted as high as 30-50 m above the ground on new towers or on other existing tall structures. However, those base stations only supported a very limited number of simultaneous mobile phone and data traffic transmissions. Even with improvements in bandwidth and capacity, the expanding demand for data transmission has generally outpaced capacity with each new generation of wireless technology. Over time, the addition of small cells within a region increased network capacities while alleviating the load on the existing macrocell site. As each cell then covered a smaller area, they operated at lower power and the antennas were mounted at lower heights. One industry source[7] reports that by 2025, more than 70 million small cells will be installed worldwide, one third of which will be for 5G networks. The increase in numbers of small cells is referred to as densification.

Influence of small cells on population exposure to RF signals. Adding small cells to a network has mixed results on overall RF exposures. Their addition will increase the downlink signal levels intended to improve quality of service. Secondarily, these higher signal strengths will cause the network to reduce the power output of handsets (the uplink). Since in most cases the stronger exposure to cellphone users is from uplink signals from their own devices, the presence of small cells will generally reduce overall RF exposure to a user or a bystander (Stephan et al. 2014; Mazloum et al. 2017). However, many variables determine personal exposure to RF fields, and simple generalizations of this sort do not always apply (Lonn et al. 2004; Boursianis et al. 2012; Durrenberger et al. 2014; Plets et al. 2015; Krayni et al. 2017; Huang 2018; Zeleke et al. 2018).

RF exposure limits

For recent reviews of RF exposure limits, see Wood and Karapidis (2017) and Foster et al. (2018). In most countries, RF exposure limits are based generally on either the International Commission on Nonionizing Radiation Protection (ICNIRP) guidelines (ICNIRP 1998, 2020) or the Institute of Electrical and Electronics Engineers (IEEE) Standard C95.1-2019 (IEEE 2019). In the US, RF exposures are regulated by the Federal Communications Commission (FCC). IEEE and ICNIRP limits were last updated in 2019 and 2020, respectively. The current version of the FCC limit was approved in 1996 (FCC 1997), but in August of 2019,

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[5] Power (typically in watts or dBm) can be expressed as power delivered to the antenna from the transmitter or the effective radiated power (ERP) which includes the concentration of power in a particular direction (gain) by the antenna. In the macrocell example above, 200 watts delivered to the antenna could result in an ERP of 5 kW.

[6] Terms commonly used by wireless carriers to describe very low power base stations.

[7] https://www.smallcellforum.org/press-releases/market-status-apac-north-america-lead-network-densification-2021/. Accessed 26 September 2019.

the FCC issued a press release stating that it intends to maintain its current RF exposure safety standards, citing a statement from the Director of the US Food and Drug Administration Center for Devices and Radiological Health that "the available scientific evidence to date does not support adverse health effects in humans due to exposures at or under the current limits."[8]

Both IEEE and ICNIRP RF limits were set to protect against the possibility of a significant rise in tissue temperature (even in warm work environments) due to exhaustion of the body's normal thermoregulatory capacity (Laakso et al. 2017; Foster et al. 2018; Hirata et al. 2019). The IEEE standard sets an exposure limit, formally called the "Exposure Reference Level" (ERL); for RF fields exceeding 2 GHz, the whole-body ERL for the general public is 10 W m^{-2}. The scientific basis of the limits is supported by reviews of the scientific literature by expert panels convened by health agencies or other official entities. For example, Section C1 of IEEE C95.1-2019 cites 20 reviews through 2017 that found no evidence of health hazards from exposures to RF energy at levels below current limits and identified "...no accepted theoretical mechanisms exist that would suggest the existence of such effects." The US Food and Drug Administration (FDA) published an in-depth review of epidemiology and laboratory studies on RF relevant to cancer published between 2008 and 2018 with selected updates through August 2019; the frequencies used in these studies were almost all between ~800-2,500 MHz, which cover 2-4G cellular frequencies. The FDA concluded (US FDA 2020): "Based on the studies that are described in detail in this report, there is insufficient evidence to support a causal association between RFR exposure and tumorigenesis. There is a lack of clear dose response relationship, a lack of consistent findings or specificity, and a lack of biological mechanistic plausibility."

Well-established hazards of millimeter waves include thermal pain in the skin (with a threshold temperature of about 44 °C) and, if the temperature is maintained at high levels (generally above 43 °C) for minutes or more, burns or other thermal damage to the skin and cornea could occur (Foster and Morrissey 2011; Sienkiewicz et al. 2016). Such hazards require exposures far above IEEE and ICNIRP exposure limits.

While most countries have adopted limits based on ICNIRP or IEEE, several cities (and even a few countries) have established their own "precautionary" limits based on a philosophy of minimizing exposure to avoid as-yet unproven hazards and are motivated in part by social concerns about RF technology. This contrasts with ICES and ICNIRP exposure limits (versions of which are adopted in most countries) that are designed to protect against known hazards (Foster et al. 2018a). Compliance of 5G base stations with regulatory limits may be further complicated in some countries that have adopted such lower "precautionary" limits (Foster et al. 2018). For example, exposure limits in Switzerland and Italy at frequencies relevant to current cellular base stations are 100 times lower than ICNIRP limits, while in India they are 10 times lower. The implications of these very restrictive limits on the deployment of new 5G base stations is under review (Chiaraviglio et al. 2018; ITU 2018).

Public exposure to RF signals from cell phone (wireless) networks

There are two distinct issues related to the public's exposure to RF fields from cellular networks. One is compliance of transmitting facilities with regulatory limits, which may be an issue in the immediate vicinity of base station antennas. The second concerns the distribution of exposure across the general population, which is relevant to addressing potential public health impacts.

Exposure from base stations. In nearly all publicly accessible locations, RF exposures from cellular base stations are small fractions of IEEE or ICNIRP exposure limits (Henderson and Bangay 2006; Bolte and Eikelboom 2012; Rowley and Joyner 2012; Estenberg and Augustsson 2014; Gajsek et al. 2015; Chiaramello et al. 2019; Jalilian et al. 2019; Velghe et al. 2019). This is not likely to change when 5G systems are installed; however, exposures may be higher near base station antennas, but wireless carriers are still obligated legally to ensure that transmitting facilities comply with regulatory limits. Issues related to compliance are quite possible in countries that have adopted "precautionary" limits that are considerably lower than those in internationally accepted guidelines and standards (Foster et al. 2018).

A recent analysis indicates that the proliferation of base stations, independent of other factors, will lower exposure levels because, in an expanded network of base stations, each cell will require lower fields in its territory to still function properly (Chiaraviglio et al. 2019). However, a key difference between 2G/3G/4G and 5G systems is that RF signals from present and older-generation systems remain in a fixed (or static) spatial pattern, whereas 5G antennas can be configured to transmit multiple beams that are steered toward individual users as they move about within a base station's coverage area. Such antennas are often referred to as beamforming or "smart" antennas. Importantly, the term 5G may encompass either static antenna beams or beamforming antennas.

Thus, even if a 5G base station that uses beamforming technology were to transmit more total power than a comparable 4G station, that power could be divided among

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[8] Press release, Chairman Pai proposes to maintain current radiofrequency exposure safety standards, 8 August 2019 https://docs.fcc.gov/public/attachments/DOC-358968A1.pdf. Accessed 14 June 2020.

multiple narrowly focused beams, each propagating in a different direction. The net effect is that 5G beamforming systems will have the capacity to provide high-quality communications through the more efficient use of transmitter power that can steer signals toward specific users. Field levels within other (off-beam) areas having no users would be sharply lower than those from a typical 4G base station; and since the 5G beam will exist only while communicating with a user, the long-term time-averaged exposure levels will also be lower.

Exposure levels from 5G base stations are under study by several groups, mainly to improve methods to assure their compliance with health and safety guidelines. Assessments have included exposures from stations employing beamforming antennas, as well as exposures from small cells that use stationary beams (Degirmenci et al. 2016; IEC 2017; Mazloum et al. 2017; Baracca et al. 2018; Kopacz and Heberling 2019).

Compliance distance is the distance from an antenna beyond which RF exposures cannot exceed applicable exposure limits. Wireless technology manufacturer Ericsson is one of the few firms presently selling 5G base station equipment. At a recent conference, an Ericsson RF safety expert presented calculations for two example cases (in terms of a site's total radiated energy) for deployment of 5G base stations (Törnevik 2017). One was a small cell radio with eight beams transmitting collectively less than 1 W at 28 GHz, which had a calculated public exposure compliance distance of 1.5 m in the boresight direction. The second was a macrocell site with a 200-W, 3.5-GHz 5G transmitter co-located with a group of 2G, 3G, and 4G antennas. In this case, the public exposure compliance distance when combined with the output of the 2G, 3G, and 4G emissions was 25 m. This evaluation was conducted assuming that all the antennas were transmitting at maximum power simultaneously, which is an extremely conservative assumption. Had the 200-W 5G macro cell radio existed in isolation, and had the actual maximum time-averaged power been considered, the compliance distance would have been substantially less, or about 11 m [see IEC TR 62669 (2019), clause 15]. For such a macrocell antenna array mounted on a tower or above a rooftop, this compliance distance is achievable, as the general public cannot, or in the case of a rooftop would not, be allowed (by the use signage and physical or indicative barriers) to approach within that distance.

Environmental exposures to RF. In urban areas in the US and Europe, environmental RF exposures come mainly from three sources: downlink signals from cellular base stations, uplink signals from cell phones operated near the body, and the signals from broadcast transmitters in the area (e.g., AM and FM radio and TV broadcasting facilities). Other sources such as Wi-Fi, other communications systems, and some household appliances contribute greater or lesser amounts to the total exposure depending on local circumstances. Dürrenberger et al. noted that the dramatic increase in data traffic in the coming decades added to the emergence of smart electrical grids will alter exposure characteristics throughout the population (Dürrenberger et al. 2014). Thus, it seems apparent that extrapolating from the current exposure patterns to those in the future is not possible with any certainty. (Note: The smart grid has been defined as, "At its core, smart grid represents the transformational application of information and communications technology to a more efficient and effective electric system" (Widergren and Pratt 2016).

A recent meta-analysis of RF exposure levels in European cities found RF exposure levels over a broad frequency range to be generally below 1 V m^{-1} (< 3 mW m^{-2}), with the highest mean exposures found in environments associated with electric rail transportation (~10 mW m^{-2}), i.e., inside rail cars, chiefly due to cell phone use by passengers. These investigators reported "no obvious temporal trend" in the public's overall RF exposure between 2005 and 2013 and suggested that increasing efficiency in transmitting data and reductions in output power of wireless devices may have offset a possible increase in exposure due to the rapid increase in data traffic (Sagar et al. 2018).

Evidence regarding the relative contributions of uplink and downlink wireless signals to population exposure has evolved over time and depends on many factors, including density of wireless facilities typically indicated by whether the exposures occur in an urban or rural environment. Birks et al. surveyed 529 children aged 8–18 y in five European countries and reported a median RF exposure level from all sources of 75 μW m^{-2}, with downlink exposures (from base stations) somewhat higher on the average than uplink exposures (from by-stander cell phones and excluding exposure from one's own cell phone) (Birks et al. 2018). Another recent survey in five urban areas in Belgium also found generally higher downlink than uplink signals (Velghe et al. 2019).

The surveys performed with subjects carrying RF monitors measured uplink exposures from nearby cell phones but were unable to evaluate exposure from one's own cell phone placed close to the body. While the results of these and other surveys show considerable variability in RF exposures from diverse sources, they also demonstrate that in virtually all cases the measured exposures were a small fraction of accepted international limits. None of the surveys cited above considered occupational exposures, whose assessments would require different approaches than those used in studies among the general public.

Recently, an exposure model was developed to assess personal exposures associated with the newly installed 3.6 GHz cellular system in Switzerland (Kuehn et al. 2019). This system operates under a 5G protocol and served in this exposure analysis as a surrogate for future 5G networks, expected to operate at higher millimeter-wave frequencies. The study considered various conditions, such as the amount of one's use of a cell phone, location (urban, suburban, or rural), a base station's area of coverage, and the extent of indoor coverage. The key finding was that "Except for non-users...total exposure is dominated by the person's own mobile device." In other words, exposure from one's own uplink, which will increase with the amounts of data transmitted, is expected to significantly exceed exposures from downlinks and base stations. Exposures for non-users would increase marginally under the scenarios examined.

So far, no comprehensive surveys of environmental 5G signals have been conducted; few 5G networks are presently in operation, and those are largely demonstration projects transmitting at less than full capacity. Nevertheless, the designs of 5G networks are constrained by the same requirements that apply to previous generations of cellular systems: to provide a signal that is strong enough to be useful within a given cell but not so strong as to cause interference to users in nearby cells. Consequently, on this basis alone, one can expect that exposures from 5G networks will not differ greatly from those associated with present generation networks. In fact, most 5G systems transmitting millimeter waves will operate with only a few watts of power.

The advent of new technologies operating under the 5G standard will alter the mix of RF exposure sources and their respective frequencies. In fact, such trends are not strictly specific to 5G and have been underway with present generations of wireless networks. Contributions to exposure will also arise from other noncellular wireless networking technologies. Nevertheless, cumulative exposure levels from wireless technologies are expected to remain well below internationally accepted exposure limits.

Assessing potential biological and health effects from exposure to millimeter waves

While many bioeffects studies have been performed using RF fields in cellular bands currently in use, comparatively few studies have been done in the millimeter wave band. As shown in Fig. 2, millimeter waves (30–300 GHz) occupy the higher end of the RF frequency spectrum (3 kHz–300 GHz) just below the infrared. Like all RF energy, it is nonionizing in that the photons have insufficient energy to eject an orbital electron, break chemical bonds, and form free radicals, a potent source of damage to biological molecules including DNA.

Since the 1960s, thousands of studies have been conducted to address possible biological and health effects from exposure to RF fields, including frequencies used by wireless communications (Fig. 3). The studies range from epidemiologic investigations of potential risks among the public and occupational populations to experimental studies aimed at uncovering biological effects of RF energy and their biophysical basis. The number of bioeffect studies using millimeter waves is a small but growing fraction of this literature. For example, roughly 100 experimental studies have been reported concerning biological effects of millimeter waves.

The penetration of RF energy into a body decreases with increasing frequency. Beyond about ~3-4 GHz, RF waves have a penetration depth into the skin of <10 mm, and beyond ~20-30 GHz the depth is <1 mm. Consequently, whole-body heating is not a concern for millimeter wave exposure because the deposition of RF energy is confined to the outermost layers of the body. The report cited above (Kuehn et al. 2019) of an exposure model to estimate future exposures from 5G in Switzerland also reported that, due to a smaller penetration depth at 3.6 GHz, the rate of RF

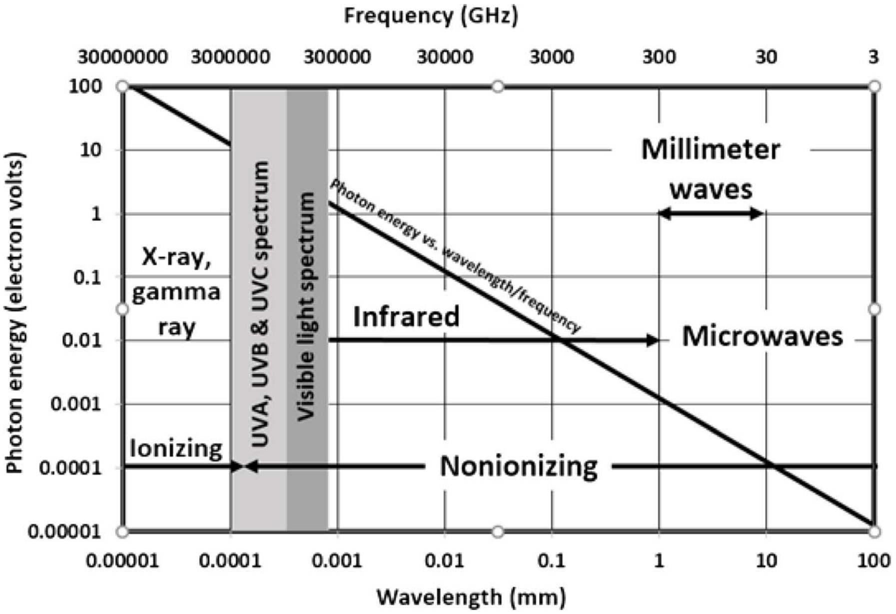

Fig. 2. Photon energy vs. wavelength (or frequency). The horizontal arrows indicate different parts of the electromagnetic spectrum.

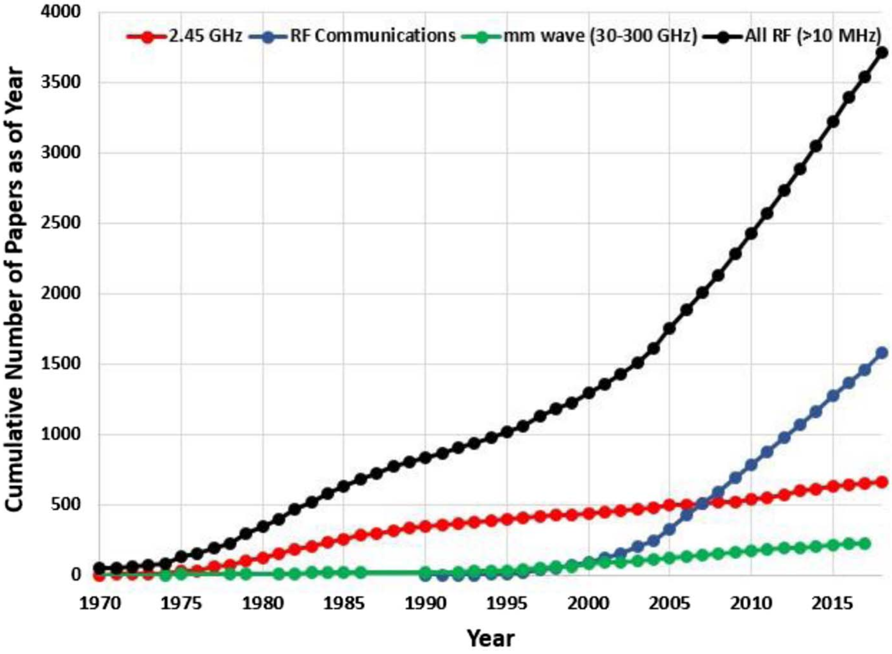

Fig. 3. Research papers on radio frequency biological effects published since 1970. Adapted from search results at EMF-Portal. Available at www.emf-portal.org. Available at: https://www.emf-portal.org/en/article/search. Date accessed 5-23-2020.

energy deposition within the brain would decrease by >6-fold compared to frequencies <1 GHz. For frequencies ≥6 GHz, IEEE Std C95.1 expresses the ERL exclusively in terms of the time-averaged power density incident upon “any 4 cm^2 of body surface.” At 30 GHz, the local IEEE public ERL is ~30 W m^{-2}. Accordingly, the obvious potential hazards of exposure to millimeter waves are thermal damage to skin and cornea.

The most extensive studies that were designed explicitly to assess potential hazards of millimeter waves were carried out in the late 1990s to early 2000s by a group at Brooks Air Force Base, TX, and their collaborators at several universities. Many of those studies involved short-term exposure (seconds to minutes) at levels far above current exposure limits and examined effects such as thresholds for thermal pain in humans (Walters et al. 2000) or corneal burns in rhesus monkeys (Chalfin et al. 2002). The Air Force supported one long-term cancer study using a well-established skin tumor model in mice with negative results (Mason et al. 2001). More recently, extensive studies on ocular damage from millimeter wave exposure at high levels have been conducted by a group at Kanazawa (Japan) Medical Center (Kojima et al. 2009; Kojima et al. 2020).

Skin and ocular injury. These and other studies demonstrate without question that exposure to millimeter waves far in excess of national and international exposure limits can be hazardous. This evidence is reviewed in IEEE C95.1-2019 Annex C.8. Both IEEE and ICNIRP limits for occupational exposures above 6 GHz were designed to limit increases in localized skin temperature to about 2-3 °C in a continually exposed person. Across the whole RF spectrum, questions about possible nonthermal (not heat related) hazards have long been discussed, but neither IEEE, ICNIRP, nor health agencies have considered the evidence for these persuasive at exposure levels below current limits (ICNIRP 2009; HC 2015; IEEE 2019; SSM 2019; US FDA 2020).

At sufficiently high intensities, millimeter waves may be particularly injurious to the lens of the eye and cornea because they are avascular with limited ability to dissipate thermal energy. This together with the limited volume of tissue in which millimeter wave energy is deposited can result in a rapid temperature increase and high peak corneal temperatures. However, these effects occur at power densities far in excess of current safety standards. For example, Kues et al. reported on chronic exposures of rabbits and rhesus monkeys to 60 GHz millimeter waves at an incident power density of 100 W m^{-2} (Kues et al. 1999). A variety of diagnostic tests was used before and after exposure to examine for damage in each subject. After single 8-h or five separate 4-h exposures, damage to the exposed eyes of rabbits and monkeys was not observed. Light and transmission electron microscopy of eye tissues failed to reveal any damage from the exposures. If damage is limited to the lenticular or corneal epithelium, it will undergo a normal repair process. However, damage to the underlying stromal layer can result in the development of clinically significant opacities (Lipshy et al. 1996). For the same incident millimeter wave power density that might result in repairable damage to the epithelium of the eye, the probability of severe stromal layer damage increases at lower frequencies because of deeper penetration of RF energy (Rosenthal et al. 1977). Note that the eye damage threshold levels reported are conservative as they were determined under anesthesia, depriving the animals of their normal convective cooling as no blinking occurred during irradiation.

Medical and bioeffects literature. The medical literature of the former Soviet Union and its former Warsaw Pact allies contains several hundred papers on various aspects of medical applications of millimeter waves, which generally involve exposure levels above existing safety limits but do not cause perceptible heating or adverse health effects (Pakhomov et al. 1998). However, this literature is difficult to access by Western readers, and such treatments have not generally been accepted by Western medicine. Moreover, these studies as a group do not meet current scientific standards of study quality. The therapeutic use of millimeter waves remains experimental in Western countries with limited research literature on the topic, and the prior Soviet results do not amount to persuasive evidence for hazards of millimeter wave exposures at levels below current limits.

Recent narrative (as opposed to more in-depth, critical systematic) reviews of millimeter wave bioeffects research vary widely in viewpoint, quality, and conclusions (Anton et al. 2015; Romanenko et al. 2017; Alekseev and Ziskin 2018; Di Ciaula 2018). COMAR was not able to identify any systematic reviews of the RF bioeffects literature for millimeter waves, either by individual authors or by expert committees under official auspices. One recent "pragmatic review" (an adaptation of a systematic review) of 94 in vivo or in vitro bioeffects studies covering the frequency range 6-100 GHz by Simkó and Mattsson (2019). About three-quarters of those studies used exposure levels above the current ICNIRP and IEEE exposure limits for the general public (10 W m^{-2}), and more than one-third used exposure levels 10 times or more above these limits.

Approximately two-thirds of the studies reviewed by Simkó and Mattsson reported statistically significant effects of some sort. However, only a small fraction of the studies (3 out of 45 in vivo studies, and 1 out of 53 in vitro studies) met all of the quality criteria that the investigators established (blinded study design, adequate exposure assessment, use of sham controls, adequate thermal control, use of positive controls where appropriate), and thus the reliability of the findings can be questioned. Moreover, there were few if any replication studies to confirm previously reported effects, and the health implications of the reported effects are unclear.

Simkó and Mattson concluded "there does not seem to be a consistent relationship between intensity (power density), exposure time, or frequency, and the effects of exposure… higher power densities do not cause more frequent responses…" Their review provided "no clear evidence" for health effects of RF exposure in the frequency range they considered, and "no clear explanation" for effects other than due to heating. However, there were "too few studies [that fulfilled] the minimal quality criteria to allow any further conclusions." A recent review by the Swedish Radiation Safety Authority concluded, "Despite the lack of established mechanism for affecting health with weak radio wave exposure, there is however need for more research covering the novel frequency domains, used for 5G" (SSM 2019). Recently the Australian Radiation Protection and Nuclear Safety Agency, in response to the expression of public concern in regard to 5G networks, stated, "There is no established evidence that low level radio wave exposure from 5G and other wireless telecommunications can affect the immune system or cause any other long term or short term health effects."[9]

Gaps in knowledge

COMAR offers these suggestions for further research on possible health and safety issues associated with MMW:

1. There is a paucity of well-done studies on health-related effects of millimeter waves. The results of most studies in the literature are of uncertain relevance to health. Many have small samples of subjects, and many lack elementary precautions to ensure reliability. Well-done studies to identify biological effects of millimeter waves of potential health significance are warranted. For example, since some future 5G systems will transmit at millimeter wave frequencies, which until now have not been prevalent in the public domain (with limited exceptions), research should examine whether skin heating from such exposures at sufficiently high levels results in adverse biological effects that differ from those due to infrared heating. Such studies should be designed with appropriate precautions to ensure validity (e.g., criteria proposed by Simkó and Mattsson) and, where appropriate, use of an "open science" model with preregistered study design (Nosek and Lakens 2014);
2. The thermal response of the body to millimeter wave exposures for extended times (10s of minutes or longer) needs further study. Above 6 GHz, present IEEE and ICNIRP exposure limits rely on theoretical/numerical models to predict transient and steady-state increases in tissue temperature. Better experimental validation of these models is needed, as well as an assessment of inter- and intra-subject variability in responses. This is particularly needed for occupational exposure limits, where extended high-level exposures of several 10s of minutes or more might result in unacceptable temperature increases in the skin under worst-case conditions (Foster et al. 2017). In terms of power density, nonoccupational

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[9] ARPANSA https://www.arpansa.gov.au/news/5g-and-other-telecommunications-do-not-affect-immune-system. Accessed 6 April 2020.

exposure limits are one-fifth of occupational limits and are well below thermally significant (or detectable) heating thresholds (Blick et al. 1997; Wu et al. 2015); and

3. Further refinements in methodology are needed to assess exposure from 5G transmitters, both environmental exposures from base stations and local exposures from transmitters used close to the body. Accurate exposure assessment of the narrow and often moving beams of transmitted signals is needed both to assess compliance with exposure limits and for health and safety research. Substantial efforts are underway on these issues by working groups of the International Committee on Electromagnetic Safety (ICES) and the International Electrotechnical Commission (IEC 2017).

CONCLUSION

The emergence of 5G cellular networks into widespread usage has attracted public attention. This development is due in part to the necessary reliance of 5G sources of MMW on many small cells installed near subscribers (densification), as well as to the introduction into the environment of RF fields from a part of the spectrum to which the public has not previously been exposed to any significant extent. Though research efforts have begun, the effect of 5G networks on population exposures to RF signals has not been as thoroughly researched as have RF exposures at lower frequencies. However, we anticipate that in all cases, exposure levels will remain well below major international exposure limits and that network operators will be aware of their obligation to maintain their systems within compliant operating parameters. When exposure levels are maintained below current exposure limits, neither health agencies nor guideline/standards setting organizations have identified hazards from exposure to millimeter waves or RF signals in lower frequency bands used in previous generation technologies. Given the limited bioeffects literature on millimeter wave exposure, however, COMAR recommends more high-quality research on MMW, together with ongoing surveillance by health agencies of relevant scientific developments. This effort should result in systematic reviews of the literature done under established protocols, with appropriate selection and evaluation criteria for research papers. Such efforts will serve the public interest and assist our society's adaptation to 5G with minimal, if any, disruption.

Finally, COMAR is comprised of career professionals who deal with environmental and health issues associated with electromagnetic exposures from across the non-ionizing spectrum, including power delivery, RF broadcast, and wireless technologies. The advent of 5G technologies has been accompanied by a steady stream of media pieces expressing various opinions on 5G ranging from the ominous to the exculpatory. Given the background and commitment of its members, we feel a unique responsibility to provide an objective assessment of where 5G technologies stand with respect to health and safety issues. COMAR concludes that while we acknowledge gaps in the scientific literature, particularly for exposures at millimeter wave frequencies, the likelihood of yet unknown health hazards at exposure levels within current exposure limits is considered to be very low, if they exist at all.

Acknowledgments—This statement was prepared by the IEEE EMBS Committee on Man and Radiation (COMAR) with significant contributions from the following: Jerrold T. Bushberg, C-K Chou, Kenneth R. Foster, Robert Kavet, David P. Maxson, Richard A. Tell, and Marvin C. Ziskin. It was revised and approved by COMAR, the IEEE Engineering in Medicine and Biology Society's Committee on Man and Radiation. It represents a consensus of COMAR, a committee that is composed of experts on health and safety issues related to electromagnetic fields, from power line through microwave frequency ranges. The mission of COMAR is to disseminate authoritative information to the public relating to the safety of nonionizing electromagnetic fields and to correct misinformation that relates to public health on this topic.

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