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Research article

ON ASSESSING HEALTH RISKS RELATED TO IMPLEMENTATION OF 5G NETWORKS

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This review covers publications with their focus on analyzing methodological approaches to assessing health risks that might occur due to implementation and development of 5G communication networks. Publications were sought in such databases as Pubmed, Scopus, Web of Science, MedLine, Global Health, and Russian Science Citation Index.

Results obtained by examining exposure to electromagnetic radiofrequency radiation in animal studies have revealed carcinogenic effects in some cases. However, population studies involving large samples of humans who are active mobile communication users have not established any significant effects that may cause health impairments. At the same time, some peculiar features of the 5G technology should be considered including extremely high network density, new scenarios of locating base stations, multiplicity of 5G-devices, networks relying on multiple different ranges (including use of decimeter-, centimeter- and millimeter-long waves). All this, together with use of signals having a great range width and new modulation types with their biological effects still remaining unknown, makes it possible to assume that an electromagnetic background in residential areas will undergo significant transformation involving growing intensity of modulated wideband electromagnetic radiation with a complex spectral structure. Conducted social surveys confirm people's concerns about health effects produced by 5G technologies. Accordingly, it is necessary to develop new methodological approaches to accomplishing investigations aimed at assessing health risks associated with implementation of such networks. This research work should consider technological peculiarities of 5G networks; results of such studies should give grounds for developing new safe standards and implementing relevant activities aimed at providing electromagnetic safety of the country population.

Keywords: *electromagnetic safety, 5G networks, literature review, electromagnetic radiofrequency radiation, animal studies, population studies, sociological surveys, perception of risks associated with electromagnetic radiation.*

At present, a new, the fifth generation of mobile communications 5G/IMT-2020 (5G)[1] is being implemented. It is considered the basis of the digital economy [1]. Given that, issues related to assessing population health risks associated with the use of these technologies are currently of particular relevance. The development of mobile networks using new technological solutions is expected to lead to a significant increase in mobile traffic, which is associated with the growing consumption of video services, a significant increase in the number of mobile devices connected to the network, increased use of appli-

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[1] International Mobile Telecommunications-2020 (IMT-2020 Standard) is a set of requirements issued by the Radiocommunication Sector of International Telecommunication Union (ITU-R) in 2015 for 5G networks, devices and services.

cations, online games and their updates. One of the most important functions performed by introducing and developing 5G networks is the use of the Internet of Things (IoT), i.e., a system for transmitting data between physical objects (‘things’) that will be equipped with special technologies enabling them to interact with each other and with the external environment, in many cases, without human intervention [2, 3]. It is also planned to continuously increase the number of such devices operating in the Internet.

5G networks have a different architecture from previous generations of mobile communications. They require a higher density of base stations and access points that generate electromagnetic radiation and provide a variety of wireless services. The evolution from 4G to 5G and then to 6G is accompanied by an increasing number of user devices per unit area. In 5G networks (IMT-2020), this number can reach up to 1 million devices per square kilometer, and in future 6G networks, it can increase to ten million devices [4]. Due to such a high density of user devices, the total electromagnetic background in 5G/6G networks may exceed permissible limits and become hazardous to health [5, 6].

The goal of this literature review is to analyze the results of different types of studies aimed at assessing the effects of electromagnetic fields (EMF) using 5G engineering knowledge, to consider methodological approaches to assessing health risks from 5G exposure, and to discuss directions for improving the methodology for conducting research on the effects produced by these new format networks.

Materials and methods. This study employs a literature analysis method, which has been used to prepare a review of scientific publications dedicated to the effects of EMF, including fifth-generation (5G) networks. The literature analysis aims to provide a systematic assessment of the literature identifying key trends, critical points, and gaps in the available scientific data. Literature was searched and analyzed using the following scientific databases: PubMed, Scopus, Web of Science, MedLine, Global Health, and the Russian Science Citation Index (RSCI).

The final inclusion of literature sources in the review was based on the following criteria.

Subject matter: studies related to the effects of EMF, particularly 5G networks, with a focus on human health.

Research type: selection covered both scientific articles presenting empirical research result and review papers, including systematic reviews and meta-analyses, published in peer-reviewed journals.

Language of publication: works published in English and Russian.

Publication period: The time frame was limited to studies published since 2000 to the present with a preference for papers published in the last five years in order to include the most recent data and trends.

During the selection process, 125 scientific sources were analyzed, of which 73 publications were included in the review based on the inclusion criteria. Each paper was analyzed in terms of methodology, results, and conclusions. In addition, a comparative analysis of the findings and a justification of the conclusions, based on the data contained in the publications, was made in the context of different types of studies on EMF and 5G.

Results and discussion. ***5G networks and population health.*** Assessing the health risks associated with 5G involves several disciplines, including biology, medicine, physics, economics, and law. However, research within each specific discipline tends to focus on a particular area with little attention to the other aspects. For instance, medical studies are generally dedicated to evaluating a potential relationship between EMF exposure and occurrence of disease, with little emphasis on experimental conditions. However, experimental conditions are often conservative and are far from representative of real-world exposure scenarios of next-generation wireless devices. Therefore, assessing the health risks associated with 5G exposure does not appear to be an easy task.

The question of possible health effects from exposure to radiofrequency (RF) energy is a matter of debate within the scientific community, but there is no conclusive evidence to date that significant risks exist. This highlights the need for further research and discussion in this area. For example, incidence of brain-related diseases, including higher nervous system disorders, mental health issues, and brain tumors is of increasing concern to society. The main possible effects on human health that can result from RF exposure are listed in Table 1.

Thus, exposure to RF-EMF could hypothetically lead to several types of health effects but the use of 5G equipment under realistic conditions is not expected to cause effects such as skin lesions, eye damage, and effects on glucose metabolism, as these phenomena are only observed at electromagnetic field levels that significantly exceed those produced by 5G equipment. The link between 5G and male fertility and electromagnetic hypersensitivity has not been scientifically proven [26, 27].

Next, we examine medical studies on the health effects of RF-EMF conducted on animals as well as population-based and sociological studies, the results of which may be relevant in studying implementation of 5G networks.

Animal-based studies. Over the past decades, numerous animal studies (for example, mice and / or rats) have been conducted to replicate RF-EMF exposure and to analyze the potential health effects associated with such exposure [28–31 and others]. However, it is worth noting that many of these studies have several shortcomings, including relatively small sample sizes, which limit the statistical power of the findings [32, 33], and insufficient experimental duration [33, 34] which call into question the long-term relevance of the

Table 1

Possible main consequences for human health can result from RF exposure

The possible consequences for human health	Description
Cancer	In 2010, based on an analysis of epidemiological studies, the International Agency for Research on Cancer (IARC) classified non-ionizing RF radiation from mobile phones as "Possibly carcinogenic to humans," placing it in category 2B [7, 8]. Research involving rats [9–12 and others] has also indicated a statistically significant increase in the risk of brain tumors, heart glial tumors, and parotid gland tumors linked to RF exposure.
Impact on the skin	Exposure to high power density RF radiation can raise the temperature of the affected body tissues [13]. Nevertheless, the human body's thermoregulation mechanisms can often accommodate modest localized heating. The significant RF absorption may cause a warming sensation on the skin, potentially resulting in mild skin burns [14].
Eye damage	Exposure to high levels of RF radiation with sufficiently high energy flux densities can lead to some ocular effects [15], including retinal damage, cataracts, and cornea problems.
Glucose metabolism	RF radiation can affect glucose metabolism in human cells [16], which can occur in the organs exposed to high levels of EMF, such as the brain.
Male fertility	Exposure to high levels of RF radiation may lead to a series of negative consequences for male reproductive health [17–19 and others], primarily a decrease in sperm fertility. However, the link between such effects and RF exposure from communication equipment has not been conclusively proven.
Electromagnetic hypersensitivity	Some studies (see, for example, [20–22]) have reported that people may associate symptoms such as headaches, stress, fatigue, sleep disturbances, heart pain, and increased blood pressure with RF exposure. Other studies (e.g., [23–25, and others]) have not shown a connection between these symptoms and levels of RF radiation, indicating that, to date, such a relationship has not been reliably confirmed.

results. To address these concerns, several international bodies, such as the World Health Organization and the National Toxicology Program (NTP), have established guidelines to ensure the quality of animal-based research investigating the development of serious diseases, particularly cancer [35–39]. These guidelines specify essential parameters, including a minimum of 50 animals per group for statistical robustness, recommended study duration of two to three years, and a requirement for at least three different levels of EMF intensity [40].

In light of these standards, noteworthy research efforts that meet these criteria include those conducted by the NTP [9, 10] and by the Ramazzini Institute [11].

The NTP studies [9, 10] are some of the longest experimental research to date aimed at evaluating the effects of RF-EMF on animals. These studies focused on 2G technology, but their results are often cited by opponents of 5G network deployment. In the NTP experiments, rats were divided into several groups and exposed to different levels of EMF for several hours a day until they died of natural causes. The experiment lasted for two years and included an initial assessment after the first 28 days and a final assessment at the end of the study. The RF devices used to generate the EMF used frequencies in the sub-GHz band for [9] and in the mid-band (1–6 GHz) for [10]. The radiated power of the RF devices was adjusted to achieve the specified exposure level in the chamber. Regular monitoring of the EMF levels was performed in each chamber to ensure compliance with the parameters set for the experimental conditions.

According to the findings of the study at sub-GHz frequency [9], carcinogenic activity was observed in Sprague-Dawley male rats, mainly manifested by the development of malignant schwannoma of the heart and other tumors (for example, malignant gliomas of the brain). At the same time, these effects were not observed in female rats. In the mid-band frequencies experiment [10], no clear signs of tumors were found in male or female rats. It is also important to note that the work [41] analyzes the results of the studies [9, 10] and concludes that RF exposure may contribute to an increase in DNA damage.

The Ramazzini Institute conducted a study to assess the impact of RF radiation on Sprague-Dawley rats [11]. The rats were exposed to RF-EMF exposure for several hours per day from prenatal life until death. According to the authors, their findings confirm the results of the NTP studies [9, 10] and previous epidemiological studies on mobile phones [42, 43, etc.], calling for a review of the IARC classification of RF radiation [8].

Next, this article examines the conducted animal studies in the context of 5G communications. 5G will operate in three main frequency bands:

1. sub-GHz band (< 1 GHz);
2. mid-band (1–6 GHz);
3. millimeter waves (30 GHz and above).

Research conducted by the NTP [9, 10] has focused on frequencies within both the sub-GHz band and mid-band frequencies. It is important to highlight that the 900 MHz frequency referenced in one of these studies [9] is very similar to the sub-GHz band used in the 5G technology; for example, Italy designates this frequency at 700 MHz. In addition, another study [10] used a frequency of 1900 MHz, which is related to 5G services in several nations, including the United States, although countries like Italy have opted for different designations. For instance, the Ramazzini Institute's research [11] used a frequency of 1800 MHz, which can be likened to mid-band frequencies related to 5G.

However, none of the studies [9–11] investigates the impact of frequencies within the millimeter-wave spectrum. The frequencies in this range exhibit distinct characteristics as they tend to penetrate body tissues less effectively than microwaves. However, it is essential to recognize that the studies produced by the NTP have primarily centered on 2G technologies, making the use of millimeter-wave frequencies impractical in this context. Therefore, the findings from studies [9–11] can only be partially used to assess the impact of 5G technologies. Many of the research parameters [9–11] appear to be quite different from those used in 5G equipment.

Variations encompass several aspects, such as exceptionally brief distances in comparison to actual ones encountered in 5G networks; substantially elevated EMF levels that far surpass those produced by 5G devices, leading to increased radiated power; prolonged duration of exposure; fundamental methods of transmission and modulation; and whole-body specific absorption rate (SAR)[2] values that do not have a direct correlation with local SAR when utilizing genuine smartphones [2].

Consequently, the findings regarding the health impacts of RF-EMF provided by the foregoing studies cannot be directly applied to the context of actual 5G network implementations.

In this regard, ICNIRP[3] highlighted in a specific statement that the studies [9–11] do not offer a cohesive, dependable, and broadly applicable set of evidence to warrant changes in exposure guidelines. To overcome these limitations, additional research is required.

Population-based studies. Research in this category aims to examine the relationship between the presence of serious diseases (such as brain tumors) in humans and the levels of radiation exposure from base stations and mobile phones. We do not focus on population-based studies of base stations exposure because the studies conducted for previous generations of mobile communication have shown that the exposure from base stations is much lower than that from mobile devices [44, 45, etc.]. Furthermore, the impact of base stations decreases significantly as users move away from the station [46–48, etc.]. Previous population-based studies [49, etc.] by the American Cancer Society [50] have not found a causal relationship between base station exposure and increased risk of tumor development. Nonetheless, given the deployment of 5G technology, characterized by an increasing number of base stations and their location in close proximity to each other [51, 52], it is important to note that questions regarding the impact of such stations on public health require further rigorous analysis. Progress in this area strongly underscores the necessity for research and discussion on the potential consequences of overall exposure.

Mobile phones are a well-known source of RF-EMF exposure in the vicinity of users (see, for example, [44, 45]). Therefore, we focus on population-based studies aimed at establishing causal relationships between tumor incidence and exposure to mobile phones. The main studies conducted in the past are also relevant in the context of 5G.

<u>INTERPHONE study</u> [53, 54] was coordinated by IARC. The study, based on the case-control approach, was carried out in thirteen countries in 2000–2012. The aim of the project was to study the impact of mobile phone use in people with severe diseases (e.g. glioma, meningioma, and acoustic neurinoma). The number of people involved in the study was of great importance involving more than 5,000 patients diagnosed with glioma or meningioma and 1,000 patients diagnosed with acoustic neurinoma. In addition, a control group was also considered which included people who did not have any of these tumor types.

The study used such methods as personal interviews and validation studies to obtain the most accurate data on mobile phone use, including the duration and frequency of the calls,

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[2] SAR is the specific absorption rate of electromagnetic energy. This indicator determines how much radiation a person receives in one second while using a smartphone. The SAR level is standardized in most countries and is used to assess potential health risks.

[3] ICNIRP (International Commission on Non-Ionizing Radiation Protection) is an independent organization officially recognized by the World Health Organization (WHO). Its main goal is to investigate the health risks associated with exposure to non-ionizing radiation and to provide recommendations for limiting exposure to minimize potential health risks.

age, and other relevant information (e.g. network operator, phone model, location of calls, user mobility, use of headset or hands-free function).

The results [53, 54] generally showed no significant association between mobile phone use and the risk of glioma, meningioma or acoustic neuroma. Some increase in glioma risk was found at high levels of RF-EMF exposure. Unfortunately, the various data errors make a more nuanced interpretation of these findings difficult.

Danish cohort study [55] was aimed at identifying a possible increase in the risk of tumor development in people who have a subscription to a mobile phone operator. The comparison group was the rest of the population without such a subscription. The study included two phases, starting with the first wave in 1982–1995 [40] and ending with the last one, covering the period 1990–2007 [55]. Despite a very large sample size (the number of subscribers in [55] exceeds 380,000), the study showed no link between the use of mobile phones, even if used for longer than thirteen years, and the risk of developing central nervous system tumors.

A large-scale project studying women's health [56] involved the respondents completing a questionnaire sent by mail. The study surveyed 1.3 million middle-aged women in the UK at various times during 1999–2009. The survey included questions aimed at assessing the impact of mobile phones, which were asked twice during the study period. The results showed no significant links between the frequency of mobile phone use and increased incidence of central nervous system tumors, or glioma, meningioma.

Next, we consider population-based studies [53–56] from the *perspective of evaluating the impact of 5G communication technology*. Table 2 summarizes the main parameters used in previous studies and how these parameters should be modified or supplemented when considering 5G equipment.

It should be noted that the assessment was conducted using traditional methods such as surveys, face-to-face/distance interviews, and (in some cases) the analysis of log files available from mobile network operators [53–56]. However, the spectrum of 5G services encompasses a variety of different functions such as data exchange and voice communications, so the measurement of mobile device activity cannot be based solely on data obtained from surveys and / or interviews. To obtain such information, it is advisable to install special

Table 2

Comparison of key parameters used in population studies [53–56] with those relevant in the 5G context

Parameters	Population-based studies	5G communication
Assessment	Questionnaires, personal interviews, long-distance interviews, mobile operator logbook	Cloud application, mobile operator logbook
Frequency of assessment	One-off, periodic	Uninterrupted
Type of Activity	Calls	Calls, video streaming, social networking, instant messaging
Intensity of activity	Number of calls	The number of minutes spent on each app, the amount of content downloaded
Connectivity	Phone number, operator	Phone number, operator, interfaces used, frequencies used, transmission information
Phone position	Head distance, use of hands-free devices	Proximity of the phone to the user, phone handling
Phone location	Country, place of residence	Country, place of residence, mobility of users
Phone information	Device model	Device model

user applications on phones that automatically transmit the measured data in a controlled cloud environment. In case this approach cannot be implemented (for example, due to privacy concerns), researchers should use files provided by mobile operators.

Other studies [53–56] with their focus on assessing frequency assume that user activity information is extracted either at the end of the considered period or on a periodic basis. In contrast, 5G requires continuous activity monitoring because of the strong temporal variations for data exchanged in applications installed on a 5G smartphone.

Finally, the methodology of the above studies focuses mainly on monitoring call duration. In this context, it seems very important to note that although 5G networks still provide voice services, the range of functions demanded by modern users is much broader, while voice communication has increasingly lost its leading position in recent times. Accordingly, research should monitor the time spent not only on call duration, but also, for example, on functions such as video streaming, social networking and instant messaging. Obtaining such data will enable creating the most accurate user profile, including exposure information for each type of service. In the context of 5G studies, it seems extremely important to record time spent on each application and to track the amount of transferred data.

Population-based studies typically take into account key characteristics such as phone number and mobile network operator. In the context of 5G research, this information should be supplemented by considering the usage time of each standard (for example, 5G, 4G, Wi-Fi). Another important characteristic relates to used frequencies (such as sub GHz, mid-band, millimeter waves) and indicators of performed handovers (which may influence the exposure).

Studies [53–56] use simple metrics such as distance to the head and use of speakerphone. In the case of 5G, it is important to take into account the position of the phone relative to the head/chest or other parts of the body. In addition, as mobile devices are used in different ways (e.g., for conversations, video viewing, text messaging, self-recording, etc.), it is also important to consider how the phone is held (for example, with one hand or two hands, in a vertical or horizontal position). Ultimately, this type of research identifies the user's location (in relation to the country, area of residence). These data can then be used, for example, to categorize users by area type (urban/rural). In the context of 5G, the mobility of users plays a key role and it is very important to ensure that this factor is also taken into account. Finally, when conducting population-based studies, one should also consider the model of the mobile device. As the exposure of the phone varies depending on the model, these data should also be collected when considering 5G equipment.

Thus, despite the extensive population-based studies conducted to assess the impact of mobile devices in legacy generation networks, their findings do not fully generalize to 5G. Consequently, a new set of population-based studies specifically focused on 5G is needed. This step requires a radical change in research methodology taking into account the parameters that need to be considered when making measurements and analyzing the obtained data.

Sociological studies. Informing the public about health risks has traditionally been based on calculating mortality estimates and publishing the resulting data in the hope that this will reduce anxiety. However, in many cases, even when experts and the public saw the results of the same estimates, they still disagreed about the magnitude of the perceived risks. This disagreement arose because members of the public based their perceptions of risk on the impact of multiple factors in addition to those objectively studied.

The study [57] was conducted to identify factors influencing public perception of the risks associated with EMF from 5G base stations. It showed that EMF from 5G base stations was perceived as a moderate health risk. The level of perceived risk was comparable to the perception of EMF risks from mobile phones, higher than the perception of risks from household chemicals, but lower than the perception of risks from cigarette smoking. In addition, the perceived risk of EMF from 5G base stations was most closely associated with the perceived risk of EMF from mobile phones and least associated with the perceived risk of drinking contaminated water.

Risk perception assessments showed a significant relationship with the sex of the subjects, assessment of how effectively the state policy was implemented, as well as the subjective perceptions of potential threats and health consequences associated with EMF exposure. Frederik Freidenstein et al. [58] found that a higher level of perception of RF-EMF exposure was associated with increased risk perception. Research also suggests that women tend to perceive risks as more serious than men do. A lower level of trust in government policies is also associated with an increased perception of risk from EMF sources. In addition, Kyunghee Kim et al. [59] found that people who scored higher on the dimensions of "personal knowledge" and "seriousness of risk to future generations" also had higher risk perception scores for mobile phone EMF.

Sociological studies have also identified factors that are associated with a lower perception of EMI risk from 5G base stations. Risk perception scores were lower in the 20–29 age group, current smokers, and non-drinkers. It has also been found [60] that older people perceive health risks as more serious than younger people. In addition, an increased sense of control was associated with lower risk perception [61]. In the study [57], the researchers hypothesized that placing a mobile phone charger nearby during sleep would lead to a lower risk perception because such behavior indicates indifference to EMF exposure; however, they found no significant association.

Marie-Eve Cousin and Michael Siegrist [62] showed that reading a brochure on mobile communication improved the objective knowledge of urban residents in Switzerland, but this came at the cost of increased anxiety. However, Liesbeth Klaassen et al. [63] reported that providing the public with information on EMF exposure improved knowledge and reduced risk perception. The authors of the study [57] constructed a multiple linear regression which showed that increased knowledge was associated with increased risk perception. This suggests that, obviously, subjects with a higher risk perception were apparently more active in gathering relevant information by relying on authoritative and trusted sources.

Methodological approaches to assessing the population health risk from 5G networks exposure. The main regulatory document guiding the assessment of health risks to the population from exposure to electromagnetic radiation is MR 2.1.10.0061-12[4] [4]. These methodical guidelines provide a systematized approach to assessing the impact of EMF on human health and may be useful for the initial risk assessment of EMF exposure from 5G networks. Nevertheless, it is important to take into account some clarifications and limitations when applying these guidelines in this area.

MR 2.1.10.0061-12 covers the frequency band up to 300 GHz, which includes frequen-

[4] MR 2.1.10.0061-12. Otsenka riska dlya zdorov'ya naseleniya pri vozdeistvii peremennykh elektromagnitnykh polei (do 300 GGts) v usloviyakh naselennykh mest: Metodicheskie rekomendatsii, utv. Rukovoditelem Federal'noi sluzhby po nadzoru v sfere zashchity prav potrebitelei i blagopoluchiya cheloveka, Glavnym gosudarstvennym sanitarnym vrachom Rossiiskoi Federatsii G.G. Onishchenko 13 aprelya 2012 g. [Assessment of the risk to public health when exposed to alternating electromagnetic fields (up to 300 GHz) in populated areas: Methodical guidelines, approved by the Head of the Federal Service for Surveillance over Consumer Rights Protection and Human Wellbeing, the RF Chief Sanitary Inspector on April 13, 2012]. *KODEKS*: *electronic fund for legal and reference documentation.* Available at: https://docs.cntd.ru/document/1200095226 (May 18, 2024) (in Russian).

cies used in 5G networks. Thus, the main methodological approaches outlined in these guidelines can be applied to assess the impact of 5G. However, it is important to recognize that 5G uses frequency bands that vary over a wide spectrum, including higher frequencies than those used in previous generations of mobile communications. The parameters and characteristics of 5G networks differ significantly from previous generations of mobile communications [52, 64]. Thus, these networks use technologies such as MIMO[5] (Multiple Input Multiple Output) and small cells, which can lead to very different characteristics of EMF propagation and concentration. The research [65] also highlights that massive parallel signal processing and precise beamforming, together with the use of higher frequency bands, may cause existing measurement methods to produce significantly overestimated results when applied to 5G networks.

Thus, to achieve more accurate and informed risk assessment, it is important to conduct additional research that considers the unique parameters of 5G and includes new data from surveillance and epidemiological studies [64-66]. As a result, the scientific and methodological framework may change as new data become available, requiring adaptation of the approaches described in MR 2.1.10.0061-12.

Currently, there is paucity in publications with clear methodological approaches to assessing the health risks to the population from exposure to 5G networks. Guidelines from the International Commission on Non-Ionizing Radiation Protection (ICNIRP) have been used to develop fuzzy logic-based algorithms to assess the risks associated with non-ionizing radiation in the 5G environment [67]. Safe standards have been adapted to take account of new technological developments, and recent updates to the ICNIRP and IEEE C95.1 standards [6] have addressed concerns about millimeter band frequencies [68]. The assessment of health risks from exposure to 5G networks should include several key steps. Based on MR 2.1.10.0061-12 and the available literature on the issue of 5G exposure of the population, we can propose the following approximate algorithm.

Exposure Source Identification. Identification of EMF sources associated with 5G networks, including base stations, small cells, user devices, etc.

Exposure Assessment. Assessment of EMF levels that may occur in different 5G operating scenarios (e.g., urban, rural, and indoor environments) both at a given point in time and for the duration of their persistence. With the development of adaptive antenna technologies in 5G networks, application of statistical approaches to the assessment of maximum exposure levels from base stations, as reflected in international documents, is becoming increasingly relevant in the field of EMF hygiene assessment at the international level [64]. For Russia, this method, which focuses analyzing real exposure conditions, is new and requires an update of the regulatory framework, as well as comprehensive studies in cooperation with mobile operators, including testing methods for extrapolation of the results obtained by selective measurements.

Analysis of Health Effects Studies. A review and analysis of the available data on the potential physiological and biochemical effects of 5G radiation, including epidemiological, population-based, and animal-based studies [69, 70].

Dose-Response Assessment. A study of the relationship between the level of exposure (dose) and the observed health effects. This step involves identifying thresholds above which adverse effects may occur.

Uncertainty Assessment. The growing concern about RF-EMF cannot be ignored as

[5] MIMO (multiple-input and multiple-output) is a method for multiplying the capacity of a radio link using multiple transmission and receiving antennas to exploit multipath propagation, which deploys multiple antennas at both the transmitter and receiver to increase the quality, throughput, and capacity of the radio link.

the population is affected by greater levels of exposure due to the high density of transmitters required for 5G systems [71]. The main sources of uncertainty are inadequate and imprecise knowledge of potential hazards, difficulties in establishing thresholds for human exposure, and heterogeneity in data on EMF duration and shielding, which affects the reliability of the resulting estimates.

Final Risk Assessment. Synthesizing data and exposure information to estimate the overall risk to the population. This step may include development of models that show how effects may vary with the exposure level, exposure time, and other factors.

Recommendations for Risk Management. Formulating recommendations and strategies to minimize health risks such as setting exposure limits, monitoring population health, and education initiatives on the safe use of technologies. These recommendations are presented to management decision makers.

Monitoring and Revision. Establishing a monitoring system to track changes in technology levels and its potential impact on health with regular assessments of risk based on accumulating new data.

Health risk assessment of 5G networks is therefore multifaceted and requires integrating knowledge from different disciplines, primarily radiophysics, biology, medicine, epidemiology and sociology. The presented algorithm is useful for formulating evidence-based recommendations and policies for the use of 5G technologies providing a unified approach to assessing potential health risks to the population.

Conclusion. Conducting studies to assess the impact of 5G (and later 6G) networks on population health requires developing a new methodology based on the considered characteristics of new-generation networks. Accordingly, we cannot directly use the methodological approaches developed for 2G, 3G and 4G networks [72]. This circumstance poses new challenges for hygienic science in terms of developing a theory of hygienic regulation of RF-EMF in a complex electromagnetic environment with justification of new unified hygienic standards. Subsequent studies should pay special attention to dosimetry and temperature control of the environment during the experiment. It is also extremely important to monitor the long-term health effects associated with wireless telecommunications [73]. The results of future research will provide the basis for developing effective measures to ensure electromagnetic safety of the population and protection against the potential negative effects of 5G networks. The assessment and management of health risks from 5G networks is a multifaceted and constantly evolving process that requires an interdisciplinary approach, involvement of the scientific, medical, and technical communities, and a transparent discussion with the public. A key aspect is the integration of new scientific data into risk management strategies to ensure safety and well-being of the population.

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