Medicina Clínica 162 (2024) 387–393

MEDICINA CLINICA

www.elsevier.es/medicinaclinica

Review

Is the sustainability of exposure to non-ionizing electromagnetic radiation possible?

Irene Calvente [a], María Isabel Núñez [a,b,c,*]

[a] Research Support Unit, Biosanitary Institute of Granada (ibs.GRANADA), University Hospital Complex of Granada, Spain
[b] Department of Radiology and Physical Medicine, School of Medicine, University of Granada, Granada, Spain
[c] Biopathology and Regenerative Medicine Institute (IBIMER), University of Granada, Spain

ARTICLE INFO

Article history:
Received 13 August 2023
Accepted 8 November 2023
Available online 26 December 2023

Keywords:
Radiofrequency electromagnetic field
Exposimeter
Personal measurements
Electromagnetic pollution
Health and environmental effects
Non-ionizing radiation safety guidelines

ABSTRACT

Technological advances imply an increase in artificially generating sources of electromagnetic fields (EMF), therefore, resulting in a permanent exposure of people and the environment (electromagnetic pollution). Inconsistent results have been published considering the evaluated health effects. The purpose of this study was to review scientific literature on EMF to provide a global and retrospective perspective, on the association between human exposure to non-ionizing radiation (NIR, mainly radiofrequency-EMF) and health and environmental effects. Studies on the health effects of 5G radiation exposure have not yet been performed with sufficient statistical power, as the exposure time is still relatively short and also the latency and intensity of exposure to 5G. The safety standards only consider thermal effects, do not contemplate non-thermal effects. We consider relevant to communicate this knowledge to the general public to improve education in this field, and to healthcare professionals to prevent diseases that may result from RF-EMF exposures.

© 2023 The Author(s). Published by Elsevier España, S.L.U. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

¿Es posible la sostenibilidad de la exposición a las radiaciones electromagnéticas no ionizantes?

Palabras clave:
Campo electromagnético de radiofrecuencia
Exposímetro
Mediciones personales
Contaminación electromagnética
Efectos sobre la salud y el medio ambiente
Directrices de seguridad frente a radiaciones no ionizantes

RESUMEN

Los avances tecnológicos implican un aumento de las fuentes artificiales que generan campos electromagnéticos (CEM), esto se traduce en una exposición permanente de las personas y el medio ambiente (contaminación electromagnética) a CEM. Se han publicado resultados contradictorios en cuanto a los efectos evaluados sobre la salud. El propósito de este estudio fue revisar la literatura científica sobre CEM para proporcionar una perspectiva global y retrospectiva, sobre la asociación entre la exposición humana a la radiación no ionizante (RNI, principalmente CEM en el rango de las radiofrecuencias) y los efectos sobre la salud y el medio ambiente. Aún no se han realizado estudios sobre los efectos en la salud de la exposición a la radiación 5G con suficiente potencia estadística, ya que el tiempo de exposición es todavía relativamente corto, igual que ocurre con la latencia y la intensidad de la exposición a la 5G. Las normas de seguridad solo consideran los efectos térmicos, no contemplan los efectos no térmicos. Consideramos relevante comunicar el conocimiento actual sobre este tema tanto al público en general para mejorar la educación en este campo, como a los profesionales sanitarios para prevenir las enfermedades que puedan derivarse de las exposiciones a RF-EMF.

© 2023 El Autor(s). Publicado por Elsevier España, S.L.U. Este es un artículo Open Access bajo la licencia CC BY-NC-ND (http://creativecommons.org/licenses/by-nc-nd/4.0/).

Introduction

Electromagnetic pollution can be understood as the continuous and uncontrolled exposure to electromagnetic fields (EMF) from any emitting source of the electromagnetic spectrum (Fig. 1). It

* Corresponding author.
E-mail address: isabeln@ugr.es (M.I. Núñez).

https://doi.org/10.1016/j.medcli.2023.11.011
0025-7753/© 2023 The Author(s). Published by Elsevier España, S.L.U. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

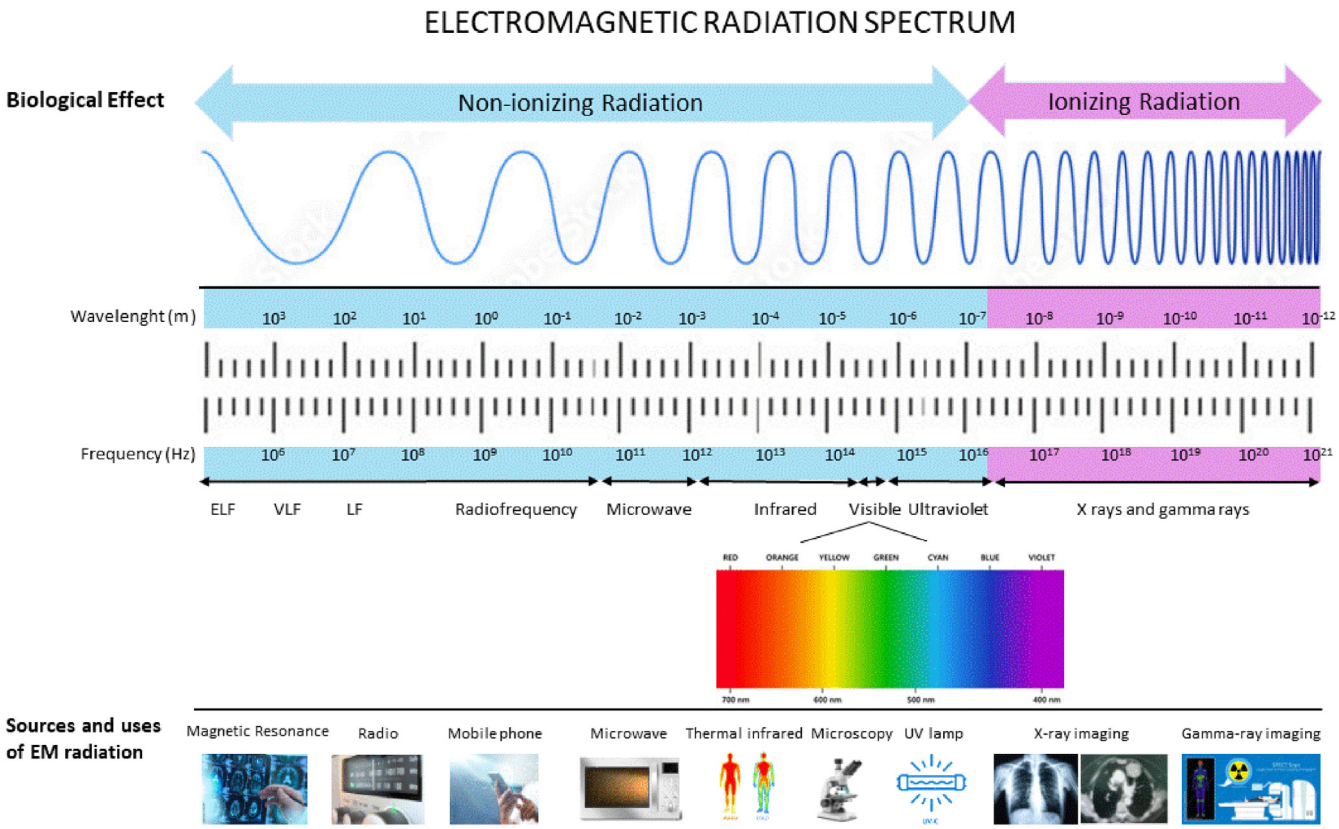

Fig. 1. Electromagnetic spectrum.

is invisible but pervasive in everyday life. Progress in science and technology are increasingly at breakneck speed. A significant proportion of the technologies developed in recent decades produce EMF radiation. In addition, the Covid-19 pandemic has accelerated key technology trends such as digital payments, telemedicine and robotics, which rely on the use of radiofrequency electromagnetic fields (RF-EMF, 100 kHz to 300 GHz).[1–3] These technological innovations include, the internet of things (IoT) with fifth generation mobile technologies or 5G and with regard to 6G, initially scheduled for implementation in 2030, but which could be brought forward in its first applications from 2026 network, Wifi 6 as a new standard for wireless connections, new applications in the medicine, industry, transport (autonomous driving and vehicle connectivity), artificial intelligence and urban planning contributing to the development of smart cities.[1,4,5] These technological advances imply an increase in artificially generating sources of EMF, therefore, resulting in a permanent exposure of people and the environment, called "electromagnetic smog" or "electromagnetic pollution". This progress has both benefits and drawbacks, as the high exposure of RF-EMF levels and the high intensity of its signal strength have an impact on human health and its impact on the environment. Electromagnetic pollution is classified as non-ionizing radiation (NIR).[2,6]

NIR refers to EMF radiation and fields with a photon energy lower than 10 eV, corresponding to frequencies lower than 3 PHz (3×10^{15} Hz) and wavelengths longer than 100 nm. It is grouped into different frequency or wavelength bands, namely ultraviolet (UV) radiation (wavelengths 100–400 nm), visible light (wavelengths 400–780 nm), infrared radiation (wavelengths 780 nm^{-1} mm), radiofrequency electromagnetic fields (frequencies 100 kHz to 300 GHz), low frequency (frequencies 1 Hz to 100 kHz) and static electric and magnetic fields (0 Hz) (Fig. 1).[7]

Moreover, to introduce a broader field of EMF study and practice, there are contrasting fields to extremely low frequency (ELF-EMF) and high frequency (HF-EMF), in fact, most applications that emit EMF are in the frequency range overhead 100 kHz up to some GHz, in the radiofrequency range as mentioned above.

As technology advances, the population is increasingly exposed to non-ionizing radiation electromagnetic fields (EMF-NIR) which has led to growing public concern over the years about the possible health and environmental effects associated with exposure.[4,8]

Depending on the frequency and strength of the radiation, EMF can have health effects at different levels. Inconsistent results have been published considering the evaluated health endpoints. Taking into account long-term effects such as carcinogenicity, the BioInitiative report concluded that there was sufficient evidence for adverse human health effects after exposure to EMF.[9] Nevertheless, scientific evidence is uneven when considering short-term effects.[10]

In 2002[11] and 2011,[12] the International Agency for Research on Cancer (IARC) classifies both ELF-EMFs (high-voltage line radiation; based on epidemiological studies of childhood leukemia) and RF-EMFs (mobile phone radiation only; based on the increased risk of glioma and acoustic neuroma) as category 2B, *i.e.* possible carcinogens,[13–15] International Commission on Non-Ionizing Radiation Protection (ICNIRP) provides guidelines on limiting exposure to electromagnetic fields. In 2020, new limits were published that replaced the 100 kHz to 300 GHz part of the ICNIRP (1998) radiofrequency (RF) guidelines, as well as the 100 kHz to 10 MHz part of the ICNIRP (2010) low-frequency guidelines.[7]

In addition, international standardization bodies, the Institute of Electrical and Electronics Engineers (IEEE), International Committee on Electromagnetic Safety (ICES) Technical Committee (TC) 95 together with and the ICNIRP, set safety guidelines to protect

people from excessive exposure to EMF but these guidelines prescribe exposure limits for people in restricted environments and for the general public in unrestricted environments. These exposure limits are not intended for patients under the care of physicians and medical professionals. They do not normally apply to the use of medical devices or implants. Exposure during medical treatment can be one or two orders of magnitude higher than the standards for the general public.[16]

Increasing concern about the possibility of adverse effects of exposure has led to investigations aimed at improving methods of measuring exposure to EMF-NIR and a large number of studies have characterized the exposure with personal, occupational and environmental measurement and in a Neonatal Medium Care Unit exposure.[8,13,14,17–26]

We are living in a great explosion of electromagnetic sources. Recent years have seen a technological boom, with a multiplication in the use of devices that emit RF-EMF, and therefore an increase in exposure to these types of NIR. In terms of human health and environmental impact, electromagnetic pollution is an increasingly important issue. Rapid technological advances have raised concerns about the potential effects of such exposure on both human health and the environment. Therefore, because we believe that the public, and especially health professionals, should be aware of the risks associated with this ever-increasing exposure, the aim of this review is to summarize the existing scientific evidence on EMF.

Methods

We reviewed scientific publications on EMF over the last two decades with a particular focus on the last five years, to provide a global and retrospective perspective, on the association between human exposure to NIR (mainly RF-EMF) and health and environmental effects. The MEDLINE/Scopus/Google Scholar database was first searched for English-Language papers, using the key words “electromagnetic field”, “radiofrequency”, “exposimeter“, “personal measurements”, “environmental”, “electropollution”, “electrosmog”, “radiation exposures”, “non-ionizing radiation”, “health effects”, “safety guidelines”, either alone or in combination.

Tools and study types: a brushstroke overview

In general, scientific fields that have detected associations between EMF and health effects have been attributed to misleading factors, potential biases and exposure misclassifications.[27,28] In recent years, the assessment of RF-EMF exposure has been significantly improved by the application of instruments to measure environmental and personal EMF exposures, thus minimizing exposure misclassification.[29]

Although, the main methods used for RF-EMF assessment include spot measurements and long-term measurements with personal or portable exposimeters and spectrum analyzers, further away there are studies than compare these measurements obtained using those devices and other new ones with different techniques (personal distributed exposimeter or body-worn distributed exposure meter) and procedures (assessments drone-based or drone-assisted measurement systems), to analyze different microenvironments (urban, rural, schools, homes, public places), spatial and temporal variability (season, day-night, different days, indoor and outdoor) and geo-referenced maps of the intensity levels registered.[2,4,8,14,17,20–24,29,30]

Both, exposure meters and spectrum analyzers, are the tools used to characterization of RF-EMF exposure, but due to the fact that exposure meters are cheaper and easier to use, they are the most commonly used tools to carry out the measurements. Analyzers show more precision to be determined frequency and power allowing the identification of each of the sources of EMF emission.[4,8,16,18,29] Portable exposimeters measure frequency band- specific emissions from FM radio, TV, base stations (downlink) and mobile phones (uplink), cordless phones, and Wi-Fi; and they have been in use since 2005.[29] However, there are several factors influencing these devices that may lead to over- or underestimation of the real exposure, such as shielding due to the influence of the proximity of a human body to the exposure meter[18,22,29] or cross-talk as another limitation of some exposure meters.[16,17,20,21]

Since the type of exposure assessment tool and associated methodology used in human epidemiological studies affects their validity, the appropriate use of RF-EMF exposure assessment tool remains an important issue.[29] Measurements must be continuous allowing the power intensity to be measured and each frequency to be distinguished according to the RF-EMF emission sources.[4]

Because of their ease of use and relatively compact size, exposimeters are thus valuable tools for assessing population exposure to RF-EMF,[17] and these tools also provide convenient objective measurements of RF-EMF exposures associated with broadcasting and telecommunications technologies. Most of these tools have been validated by recent international epidemiological studies. These tools have demonstrated their ability to provide RF-EMF exposure data for current and future human epidemiological studies.[29]

Radiofrequency electromagnetic fields exposure and health impact

Non-ionizing radiation mechanisms and study models

Technology, and RF in particular, is constantly shaping the way we live today and is ubiquitous in our daily lives. Thus, the impact of RF-EMF on human health cannot be excluded but can be minimized by limiting the level of the radiation.[31] For this reason, it is important to be aware of the impact of short and long-term (months/years) RF-EMF exposure.

Several pathways have been involved in RF-EMF biological effects including oxidative molecular damage, activation of the ERK1/2 signaling pathway and heat shock protein induction.[32] Among them, Voltage Controlled Calcium Gates (VCCGs) have been considered as relevant since these channels are responsible for the calcium ions transport across the cellular membrane being key players of the cellular homeostasis regulation.[33]

Depending on RF-EMF exposure conditions and the model of study (cells, laboratory animals and human) the effects of EMF on health yet described can be therapeutic[34,35] as well as potentially harmful.[32,36,37]

Scientific evidence on RF-EMF shows that everyday exposure to wireless devices can influence the physical, emotional and psychological health and well-being of children and adults.[38] Scientific literature shows that, while ICNIRP currently consider “low-level” exposures safe; it is becoming increasingly clear that RF exposure, not only affects endocrine and reproductive functions, but also adversely affects immune system role. In fact, it is known that RF exposure induces changes in innate and adaptive immune responses although there is some controversy on the effects of RF on immune cell physiology on humans. On the other hand, controversial results have been found focusing on the immune response in animals.[39]

Thermal and non-thermal effects

The established regulatory limits are based on false suppositions that over-heating by high power RF is the only established health effect to be avoided. Nevertheless, updated research shows that non-thermal levels of RF can cause major adverse effects such as induction of reactive oxygen species (ROS), DNA damage, car-

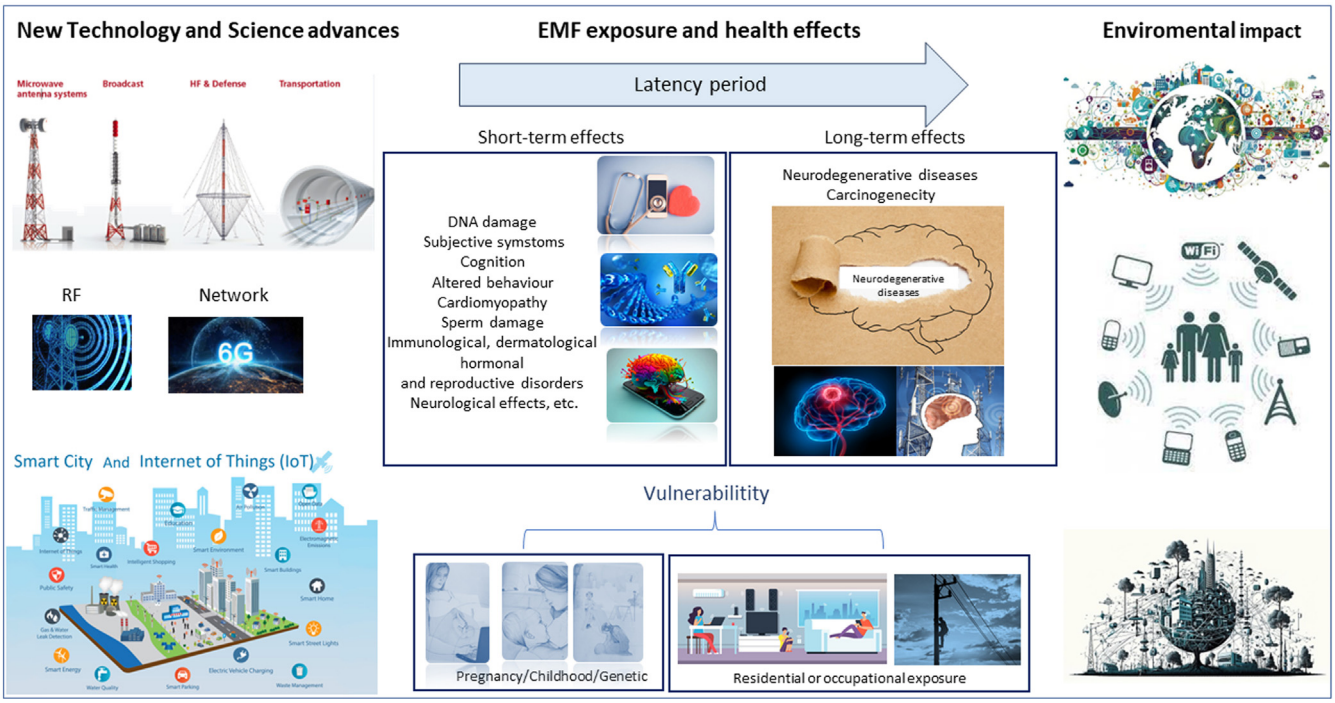

Fig. 2. Electropollution: science advances, health and environmental effects.

diomyopathy, carcinogenicity, sperm damage, memory damage, and neurological effects.[40,41] Moreover, extensive scientific evidence indicates that wireless radiation has numerous non-thermal effects on reproduction, development, and chronic diseases. There are also studies suggesting that harmful effects are greatest when exposures occur during critical stages of growth and development, including pregnancy.[42–44]

Experimental and epidemiological evidence shows that prenatal exposure to RF could be associated to impaired oogenesis and spermatogenesis, reduced volume and number of brain pyramidal cells, several neuronal impairments, ovarian dysfunction[43] and increased DNA damage in multiple organs of offspring.[44]

Therefore, two different models could be established for the determination of the impact of NIR on human health, when RF exposure is taken into account. The thermal model, which is based on threshold values of the specific absorption rate (SAR) that have been established for potentially adverse health effects. The non-thermal model relies on the ability of coherent electric fields to produce biological effects at constant temperature and has no thresholds.

Non-thermal effects have been documented by numerous studies,[38,41,45] although neither the ICNIRP nor IEEE recognize them as sufficiently established to be relevant for exposure limits. On the contrary, other expert groups such as the International Commission on the Biological Effects of Electromagnetic Fields (ICBE-EMF) and the Oceania Radiofrequency Scientific Advisory Association Inc. (ORSAA) do not share this view.[41,46]

Surprisingly, the new safety guidelines issued by ICNIRP and ICES standards make recommendations to supposedly protect against adverse human health effects from exposure to RF radiation in the frequency range 100 kHz to 300 GHz. In fact, the guidelines and standards are based on controlling whole body temperatures from rising above 1 °C or local tissue temperatures to 5 °C for short-term exposures of 6 or 30 min.[7,46–48] Therefore, the revised safety guidelines and standards demonstrate, beyond doubt, that the groups' strong convictions on nothing but heat to be concerned about RF radiation.[49]

Short and long-term effects

As with cell and animal studies, research on potential effects in humans has looked at a broad range of subjects and criteria.[50]

Many studies have been conducted in children due to their greater susceptibility to RF exposure (Fig. 2). In this sense, it is important to consider the sensitivity of children and adolescents with respect to their developing nervous system, the anatomy and physiology of their head, and the longer duration of exposure to RF from mobile devices due to their higher life expectancy compared to adults. A systematic review analyzed the physiological and health related effects of RF-EMF from wireless communication on children and adolescents in human experimental and epidemiological studies.[10] These results showed that the effects of RF on subjective symptoms (*e.g.*, headaches, dizziness, concentration and sleep problems), cognition, and behavior in children and adolescents were low to insufficient. On the other hand, the evidence from the studies on early childhood development, brain activity, cancer and physiological parameters was considered insufficient to for draw conclusions about possible effects.[10]

Various biological effects have been reported in humans in relation to non-carcinogenic adverse effects[27,51] (Fig. 2), although there is no consensus on a causal relationship with RF exposure in many cases due either to small samples sizes in the research conducted in children or because long-term exposure has not yet been evaluated by some studies.[51]

A large number of studies has been conducted to investigate the possible carcinogenicity of RF-EMF *i.e.*, including epidemiological studies, *in vivo* animal experimental and *in vitro* cell assays.[50]

Clear evidence of carcinogenicity has been found in animal studies following whole-body exposure to 2G and 3G RF radiation.[52,53] Nevertheless, it is very difficult to extrapolate the results found in animal and *in vitro* studies to those found in epidemiological studies. This is mainly due to the difficulty to regulate a great variety of possible confounders and to modify RF-EMF exposure parameters (exposure time, EMF frequency, single EMF exposure, *etc.*) in epidemiological studies. In addition, co-exposure to other toxicants

may influence the final biological effect, thus increasing the risk of adverse human health effects.

Considering carcinogenic effects, most studies on cancer risk from mobile phones have focused on brain tumors. Some authors have reported an increased incidence of high-grade tumors.[54]

In the INTERPHONE multinational case–control study, no overall increased risk of either glioma or meningioma was found to be associated with use of mobile phones. These authors suggest that bias and error prevent a causal interpretation of an increased risk of glioma at the highest exposure levels.[55] Moreover, it is also important to consider that changes in the finding of an effect could be diluted by combining participants with low and high phone use.

The MOBI-Kids project is a multinational case–control study of brain tumors conducted to assess the risk of this malignancy in young people through the use of mobile communication devices.[56] Although these results do not provide evidence of a causal association between mobile phone use and breast tumor in young people, potential sources of residual bias prevent these authors from discarding a small increase in risk due to mobile phone use. Indeed, the MOBI-Kids study of mobile phone use in Canadian children reported a doubled risk of glioblastoma multiforme with mobile phone use. The MOBI-Kids results also highlight the importance of taking into account the effect of the communication system and the anatomical location of the brain when estimating dose, and suggest that phone use is becoming a poorer proxy indicator of exposure, as the communication systems available for voice calls tend to become more complex over time.[57] This study has been criticized for methodological flaws, particularly as very few of the participants had significant exposure to mobile phones.[58] An increased risk was found in the 10–14 and 20–24 age groups, age groups. These are age groups that have lived long enough to have been more exposed than the younger children included in this study. However, there was no overall increased risk of brain tumors was reported in the temporal region in these young cases.

Several studies (*e.g.*, The Hardell group in Sweden and the French CERENAT case–control study) show an increased risk of brain tumors associated with mobile phone use.[36] The largest case–control studies on mobile phone exposure and glioma and acoustic neuroma showed significantly increased risks which tended to rise with increasing latency and cumulative duration of use, ipsilateral phone use, and earlier age at first exposure.[36] These data support the urgency of warning the population about mobile phone use and support measures to reduce as much as possible RF-EMF exposure.[36]

With regard to 5G technology, a recent review article examined 107 (1 human, 15 *in vivo*, and 91 *in vitro*) experimental studies evaluating various physiological responses to 5G mm-wave exposures.[59] This review found no confirmed evidence that low-level RF fields above 6 GHz such as those used by the 5G network are hazardous to human health. These authors suggest that epidemiological studies are needed to monitor long-term health effects in the population related to wireless telecommunication. Nevertheless, reported experimental studies of various types have shown that health and safety assessments are inconsistent in correlating biological effects with 5G mm-wave exposure.[42] It is important to note that potential chronic health or environmental effects of 5G have been poorly tracked or evaluated.

Scientific literature shows that the fourteen assumptions[41] underlying the RF exposure limits reaffirmed by ICNIRP in 2020[7] are not valid. Therefore, considering all the information gathered in this review, we believe that the application of the precautionary principle (ALARA, as low as reasonably achievable) is necessary as a strategy for RF health and safety protection. In this sense, in the prevention and treatment of RF-EMF related diseases, the role of the health care professional is crucial.

Electromagnetic pollution deserves a serious reflection

It is not only the so-called long-term effects that threaten a person's survival. These are no longer so long-term, as we have already been living with mobile devices for more than two decades. It is also the short-term effects that need to be addressed, and these are increasingly diverse and have varying degrees of impact on human quality of life.

Although this review focuses on the RF range, it is important to remember that there is a wider range of NIR exposures, *e.g.* ELF-EMF.

Particularly, vulnerable cases (children, pregnant women and electrosensitive people) should be especially protected. The immune system has a variable and limited capacity to respond to different insults. Thus, whether the outcome of RF exposure is biological or adverse health effects, depends on individual susceptibility. Due to the intrinsic immersion in EM radiation exposure, there is a remarkable difference in vulnerability compared to two decades ago.

Furthermore, current RF exposure limits do not account for potential synergistic effects due to concurrent exposure to other toxic or carcinogenic agents, the impact of pulsed radiation or frequency modulation, multiple frequencies, differences in absorption levels or susceptibility in children, or differences in individual RF sensitivity due to genetic background.

For new technologies, especially 5G, there are too many uncertainties regarding exposure to support a safety hypothesis without adequate data on health effects. Studies on the health effects of short or long-term exposure to 5G radiation in animal models or in humans have not yet been performed with sufficient statistical power, as the exposure time is still relatively short and also the latency and intensity of exposure to 5G.

Assumptions about the safety of exposures that could adversely affect human or environmental health are based on flawed assumptions using outdated exposure metrics and should be tested and validated by public health and microenvironmental protection agencies before widespread exposures occur, not after. Furthermore, it should not be ruled out that additional effects of RF radiation may occur with co-exposure to other environmental agents.

The use of technologies that make life easier has been triggered by covid, and the rising digital wave during this pandemic has been a boom that has given rise to new sectors and technologies, (EdTech, FinTech, cybersecurity), healthcare (diagnostics, virtual care, fitness), entertainment (over the top, games, social networks) and e-commerce (contactless delivery, payment methods, augmented reality). However, that the effects of such exposure will increase it is not taken into account. Limitations of the instrument, uncertainty, bias, misclassification, among others, are no longer one of the most recurring reasons for not being able to establish the possible cause–effect relationship. Most of these tools have been validated by recent international epidemiological studies. These tools have demonstrated their ability to provide RF-EMF exposure data for current and future human epidemiological studies,[29] as mentioned above.

Protocols that are increasingly well established but not agreed at international level. It would be interesting to establish common protocols in order to extrapolate the results related to RF-EMF exposure.

ICNIRP reviews safety guidelines but does not provide solutions, uses SAR, only considers thermal effects, does not consider non-thermal effects. Scientific evidence shows the importance of considering both thermal and non-thermal effects, short and long-term biological effects, and other factors. On the other hand, more frequent periodic reviews of the regulations are needed. According to ICNIRP the last one was in 2020. Even considering the leap

in technology use in 2020, should we wait as many years as now (approx. 10) for a new update?

There are countries with stricter regulations than those established by IARC that are more concerned about the effects of this type of exposure (Italy, Belgium, Austria (Salzburg), Switzerland, Russia, China).

The telephone companies considered that there could be more people in the world with mobile phones than with access to electricity and drinking water. Today, more than 67% of the world's population uses mobile devices and the technology of the future, hand in hand with these objects, awaits is just around the corner (GSMA Intelligence).

As new advances in the application of technology, particularly in the RF range, continue to develop, there is a need to systematically analyze the available evidence on potential health-related effects of RF-EMF exposure.

Since most electromagnetic waves surrounding us are invisible and unavoidable, WHO recommends prevention, but warns of another possible effect: "anxiety related to the presence of new technologies".

It is important to communicate this knowledge to the general public in order to improve education in this field, and to healthcare professional in order to prevent diseases that may result from RF-EMF exposures. These professionals must have a broad knowledge of what is happening in order to be able to provide the necessary responses to society and, in particular, to patients.

In the face of such divergent assessments of wireless RF radiation, the practice of ALARA – as low as reasonably achievable – for RF health and safety should be followed.

On the basis of the evidence presented here, is it possible to speak of sustainability in relation to electromagnetic fields?

Ethical considerations

This work does not involve the use of human subjects, therefore written informed consent is not provided.

Funding

No funding was required for this work.

Conflict of interest

There is no conflict of interests.

Acknowledgments

The authors are grateful to Myriam Ruiz for editorial assistance.

References

1. Modgil S, Dwivedi YK, Rana NP, Gupta S, Kamble S. Has Covid-19 accelerated opportunities for digital entrepreneurship? An Indian perspective. Technol Forecast Soc Change. 2022;175:121415, http://dx.doi.org/10.1016/j.techfore.2021.121415.
2. Petroulakis N, Mattsson MO, Chatziadam P, Simko M, Gavrielides A, Yiorkas AM, et al. NextGEM: next-generation integrated sensing and analytical system for monitoring and assessing radiofrequency electromagnetic field exposure and health. Int J Environ Res Public Health. 2023;20:6085, http://dx.doi.org/10.3390/ijerph20126085.
3. Wang XV, Wang L. A literature survey of the robotic technologies during the COVID-19 pandemic. J Manuf Syst. 2021;60:823–36, http://dx.doi.org/10.1016/j.jmsy.2021.02.005.
4. Rivera González MX, Félix González N, López I, Ochoa Zambrano JS, Miranda Martínez A, Maestú Unturbe C. Compact exposimeter device for the characterization and recording of electromagnetic fields from 78 MHz to 6 GHz with several narrow bands (300 kHz). Sensors (Basel). 2021;21:7395, http://dx.doi.org/10.3390/s21217395.
5. Wang Q, Su M, Zhang M, Li R. Integrating digital technologies and public health to fight Covid-19 pandemic: key technologies, applications, challenges and outlook of digital healthcare. Int J Environ Res Public Health. 2021;18:6053, http://dx.doi.org/10.3390/ijerph18116053.
6. Mubashir M. Impact of electromagnetic pollution on human health and environment a case study in Pakistan Sukkur IBA. J Comput Math Sci. 2022;6:39–55, http://dx.doi.org/10.30537/sjcms.v6i2.1223.
7. ICNIRP. International commission on non-ionizing radiation protection. Guidelines for limiting exposure to electromagnetic fields (100 kHz to 300 GHz). Health Phys. 2020;118:483–524, http://dx.doi.org/10.1097/HP.0000000000001210.
8. Ramirez-Vazquez R, Gonzalez-Rubio J, Arribas E, Najera A. Characterisation of personal exposure to environmental radiofrequency electromagnetic fields in Albacete (Spain) and assessment of risk perception. Environ Res. 2019;172:109–16, http://dx.doi.org/10.1016/j.envres.2019.02.015.
9. BioInitiative Report: a rationale for a biologically-based public exposure. In: Standard for electromagnetic fields (ELF and RF); 2007, http://dx.doi.org/10.1016/j.pathophys.2009.03.004.
10. Bodewein L, Dechent D, Graefrath D, Kraus T, Krause T, Driessen S. Systematic review of the physiological and health-related effects of radiofrequency electromagnetic field exposure from wireless communication devices on children and adolescents in experimental and epidemiological human studies. PLOS ONE. 2022;17:e0268641, http://dx.doi.org/10.1371/journal.pone.0268641.
11. IARC Monographs on the Evaluation of Carcinogenic Risks to Humans. Non-ionizing Radiation, Part 1: Static and Extremely Low-frequency (ELF) Electric and Magnetic Fields. IARC Library Cataloguing in Publication Data. 2002;80:1–395.
12. IARC classifies radiofrequency electromagnetic fields as possibly carcinogenic to humans. IARC. 2011. http://www.iarc.fr/en/media-centre/pr/2011/pdfs/pr208_E.pdf.
13. Calvente I, Dávila-Arias C, Ocón-Hernández O, Pérez-Lobato R, Ramos R, Artacho-Cordón F, et al. Characterization of indoor extremely low frequency and low frequency electromagnetic fields in the INMA-Granada cohort. PLoS ONE. 2014;9:e106666, http://dx.doi.org/10.1371/journal.pone.0106666.
14. Calvente I, Fernández MF, Pérez-Lobato R, Dávila-Arias C, Ocón O, Ramos R, et al. Outdoor characterization of radio frequency electromagnetic fields in a Spanish birth cohort. Environ Res. 2015;138:136–43.
15. Deruelle F. The different sources of electromagnetic fields: dangers are not limited to physical health. Electromagn Biol Med. 2020;39:166–75, http://dx.doi.org/10.1080/15368378.2020.1737811.
16. Hirata A, Diao Y, Onishi T, Sasaki K, Ahn S, Colombi D, et al. Assessment of human exposure to electromagnetic fields: review and future directions. IEEE Trans Electromagn Compat. 2021;63:1619–30.
17. Huss A, Dongus S, Aminzadeh R, Thielens A, van den Bossche M, Van Torre P, et al. Exposure to radiofrequency electromagnetic fields: comparison of exposimeters with a novel body-worn distributed meter. Environ Int. 2021;156:106711, http://dx.doi.org/10.1016/j.envint.2021.106711.
18. Zeleke BM, Brzozek C, Bhatt CR, Abramson MJ, Croft RJ, Freudenstein F, et al. Personal exposure to radio frequency electromagnetic fields among Australian adults. Int J Environ Res Public Health. 2018;12:2234, http://dx.doi.org/10.3390/ijerph15102234.
19. Massardier-Pilonchery A, Nerrière E, Croidieu S, Ndagijimana F, Gaudaire F, Martinsons C, et al. Assessment of personal occupational exposure to radiofrequency electromagnetic fields in libraries and media libraries, using calibrated on-body exposimeters. Int J Environ Res Public Health. 2019;16:2087, http://dx.doi.org/10.3390/ijerph16122087.
20. García-Cobos FJ, Paniagua-Sánchez JM, Gordillo-Guerrero A, Marabel-Calderón C, Rufo-Pérez M, Jiménez-Barco A. Personal exposimeter coupled to a drone as a system for measuring environmental electromagnetic fields. Environ Res. 2023;216:114483, http://dx.doi.org/10.1016/j.envres.2022.114483.
21. Eeftens M, Dongus S, Bürgler A, Röösli M, ACCEDERA team. A real-world quality assessment study in six ExpoM-RF measurement devices. Environ Res. 2020;182:109049, http://dx.doi.org/10.1016/j.envres.2019.109049.
22. Paniagua JM, Rufo M, Jiménez A, Antolín A. Dimensionless coefficients for assessing human exposure to radio-frequency electromagnetic fields indoors and outdoors in urban areas. Environ Res. 2020;183:109188, http://dx.doi.org/10.1016/j.envres.2020.109188.
23. Koppel T, Ahonen M, Carlberg M, Hardell L. Very high radiofrequency radiation at Skeppsbron in Stockholm, Sweden from mobile phone base station antennas positioned close to pedestrians' heads. Environ Res. 2022;208:112627, http://dx.doi.org/10.1016/j.envres.2021.112627.
24. Velghe M, Joseph W, Debouvere S, Aminzadeh R, Martens L, Thielens A. Characterisation of spatial and temporal variability of RF-EMF exposure levels in urban environments in Flanders, Belgium. Environ Res. 2019;175:351–66, http://dx.doi.org/10.1016/j.envres.2019.05.027.
25. Calvente I, Pérez-Lobato R, Núñez MI, Ramos R, Guxens M, Villalba J, et al. Does exposure to environmental radiofrequency electromagnetic fields cause cognitive and behavioral effects in 10-year-old boys? Bioelectromagnetics. 2016;37:25–36, http://dx.doi.org/10.1002/bem.21951.
26. Yamazaki K, Ikeda-Araki A, Miyashita C, Tamura N, Yoshikawa T, Hikage T, et al. Measurement of personal radio frequency exposure in Japan: the Hokkaido study on the environment and children's health. Environ Res. 2023;216:114429, http://dx.doi.org/10.1016/j.envres.2022.114429.
27. Calvente I, Fernández MF, Villalba J, Olea N, Núñez MI. Exposure to electromagnetic fields (non-ionizing radiation) and its relationship with childhood leukemia: a systematic review. Sci Total Environ. 2010;15:3062–9.
28. Calvente I, Vázquez-Pérez A, Fernández MF, Núñez MI, Múñoz-Hoyos A. Radiofrequency exposure in the neonatal medium care unit. Environ Res. 2017;152:66–72, http://dx.doi.org/10.1016/j.envres.2016.09.019.

29. Bhatt CR, Henderson S, Brzozek C, Benke G. Instruments to measure environmental and personal radiofrequency-electromagnetic field exposures: an update. Phys Eng Sci Med. 2022;45:687–704, http://dx.doi.org/10.1007/s13246-022-01146-y.
30. Necz PP, Gyulai B, Krausz J, Varga PJ, Baross MT, Thuroczy G. Broadband and band-selective measurements of radiofrequency EM field with drone system around 5G base station. In: Proceedings of the joint annual meeting of the bioelectromagnetics society and the European BioElectromagnetics Association, vol. 190. 2021. p. 26–30, http://dx.doi.org/10.21175/rad.abstr.book.2023.34.11.
31. Hinrikus H, Koppel T, Lass J, Roosipuu P, Bachmann M. Limiting exposure to radiofrequency radiation: the principles and possible criteria for health protection. Int J Radiat Biol. 2023;99:1167–77, http://dx.doi.org/10.1080/09553002.2023.2159567.
32. Lai H, Levitt BB. Cellular and molecular effects of non-ionizing electromagnetic fields. Rev Environ Health. 2023:1–11, http://dx.doi.org/10.1515/reveh-2023-0023.
33. Panagopoulos DJ, Karabarbounis A, Yakymenko I, Chrousos GP. Human-made electromagnetic fields: ion forced-oscillation and voltage-gated ion channel dysfunction, oxidative stress and DNA damage (Review). Int J Oncol. 2021;59:1–16, http://dx.doi.org/10.3892/ijo.2021.5272.
34. Mehdizadeh R, Madjid Ansari A, Forouzesh F, Ghadirian R, Shahriari F, Shariatpanahi SP, et al. Crosstalk between non-ionizing electromagnetic fields and metastasis; EMT and hybrid E/M may explain the anticancer role of EMFs. Prog Biophys Mol Biol. 2023;10:49–58, http://dx.doi.org/10.1016/j.pbiomolbio.2023.06.003. Review.
35. Özgen M, Take G, Kaplanoğlu İ, Erdoğan D, Seymen CM. Therapeutic effects of melatonin in long-term exposure to 2100 MHz radiofrequency radiation on rat sperm characteristics. Rev Int Androl. 2023;21:100371, http://dx.doi.org/10.1016/j.androl.2023.100371.
36. Miller AB, Sears ME, Morgan LL, Davis DL, Hardell L, Oremus M, et al. Risks to health and well-being from radio-frequency radiation emitted by cell phones and other wireless devices. Front Public Health. 2019;13:223, http://dx.doi.org/10.3389/fpubh.2019.00223.
37. Davis D, Birnbaum L, Ben-Ishai P, Taylor H, Sears M, Butler T, et al. Wireless technologies, non-ionizing electromagnetic fields and children: identifying and reducing health risks. Curr Probl Pediatr Adolesc Health Care. 2023;53:101374, http://dx.doi.org/10.1016/j.cppeds.2023.101374.
38. Belpomme D, Hardell L, Belyaev I, Burgio E, Carpenter DO. Thermal and non-thermal health effects of low intensity non-ionizing radiation: an international perspective. Environ Pollut. 2018;242:643–58.
39. Yadav H, Sharma RS, Singh R. Immunotoxicity of radiofrequency radiation. Environ Pollut. 2022;309:119793, http://dx.doi.org/10.1016/j.envpol.2022.119793.
40. Parizek D, Visnovcova N, Hamza Sladicekova K, Misek J, Jakus J, et al. Electromagnetic fields – do they pose a cardiovascular risk? Physiol Res. 2023;72:199–208, http://dx.doi.org/10.33549/physiolres.934938.
41. International Commission on the Biological Effects of Electromagnetic Fields (ICBE-EMF). Scientific evidence invalidates health assumptions underlying the FCC and ICNIRP exposure limit determinations for radiofrequency radiation: implications for 5G. Environ Health. 2022;21:1–25, http://dx.doi.org/10.1186/s12940-022-00900-9.
42. English K, Lau C, Jagals P. The unique vulnerabilities of children to environmental hazards. Early-life Environ Expos Dis. 2020:103–12, http://dx.doi.org/10.1007/978-981-15-3797-4_6.
43. Alchalabi ASH, Rahim H, Aklilu E, Al-Sultan II, Aziz AR, Malek MF, et al. Histopathological changes associated with oxidative stress induced by electromagnetic waves in rats' ovarian and uterine tissues. Asian Pac J Reprod. 2016;5:301–10, http://dx.doi.org/10.1016/j.apjr. 2016.06.008.
44. Bozok S, Karaagac E, Sener D, Akakin D, Tumkaya L. The effects of long-term prenatal exposure to 900, 1800, and 2100 MHz electromagnetic field radiation on myocardial tissue of rats. Toxicol Ind Health. 2023;39:1–9, http://dx.doi.org/10.1177/07482337221139586.
45. Bandara P, Carpenter DO. Planetary electromagnetic pollution: it is time to assess its impact. Lancet Planet Health. 2018;2:e512–4, http://dx.doi.org/10.1016/S2542-5196(18)30221-3.
46. ORSAA Training Video No 9: Bio-Effect classification system. Available from: https://www.orsaa.org/effect-classification.html [accessed 26.7.23].
47. IEEE-ICES standards for safety levels with respect to human exposure to electric, magnetic, and electromagnetic fields, 0 Hz to 300 GHz (Revision of IEEE Std C95.1-2005/Incorporates IEEE Std C95.1-2019/Cor 1-2019). New York: The Institute of Electrical and Electronics Engineers Inc.; 2019:1–312. http://dx.doi.org/10.1109/IEEESTD. 2019.8859679.
48. IEEE-ICES technical committee 95. Synopsis of IEEE Std C95.1™-2019 IEEE standard for safety levels with respect to human exposure to electric, magnetic, and electromagnetic fields, 0 Hz to 300 GHz. IEEE Access. 2019;171346–56. http://dx.doi.org/10.1109/ACCESS. 2019.2954823.
49. Lin JC. Incongruities in recently revised radiofrequency exposure guidelines and standards. Environ Res. 2023;222:115369, http://dx.doi.org/10.1016/j.envres.2023.115369.
50. Gupta S, Sharma RS, Singh R. Non-ionizing radiation as possible carcinogen. Int J Environ Health Res. 2022;32:916–40, http://dx.doi.org/10.1080/09603123.2020.1806212.
51. Prlić I, Šiško J, Varnai VM, Pavelić L, Macan J, Kobešćak S, et al. Wi-Fi technology and human health impact: a brief review of current knowledge. Arh Hig Rada Toksikol. 2022;73:94–106, http://dx.doi.org/10.2478/aiht-2022-73-3402.
52. Wyde ME, Horn TL, Capstick MH, Ladbury JM, Koepke G, Wilson PF, et al. Effect of cell phone radiofrequency radiation on body temperature in rodents: pilot studies of the National Toxicology Program's reverberation chamber exposure system. Bioelectromagnetics. 2018;39:190–9, http://dx.doi.org/10.1002/bem.22116.
53. NTP/NIEHS Technical report on the toxicology and carcinogenesis studies in HSD: Sprague–Dawley SD rats exposed to whole-body radio frequency radiation at a frequency (900 MHz) and modulations (GSM and CDMA) used by cellphones. Natl Toxicol Program Tech Rep Ser. 2018;595:NTP-TR-595. http://dx.doi.org/10.22427/NTP-TR-595.
54. Philips A, Henshaw DL, Lamburn G, O'Carroll MJ. Brain tumours: rise in glioblastoma multiforme incidence in England 1995–2015 suggests an adverse environmental or lifestyle factor. J Environ Public Health. 2018;24:7910754, http://dx.doi.org/10.1155/2018/7910754.
55. The INTERPHONE Study Group. Brain tumour risk in relation to mobile telephone use: results of the INTERPHONE international case–control study. Int J Epidemiol. 2010;39:675–94, http://dx.doi.org/10.1093/ije/dyq079.
56. Castaño-Vinyals G, Sadetzki S, Vermeulen R, Momoli F, Kundi M, Merletti F, et al. Wireless phone use in childhood and adolescence and neuroepithelial brain tumours: results from the international MOBI-Kids study. Environ Int. 2022;160:107069, http://dx.doi.org/10.1016/j.envint.2021.107069.
57. Calderón C, Castaño-Vinyals G, Maslanyj M, Wiart J, Lee AK, Taki M, et al. Estimation of RF and ELF dose by anatomical location in the brain from wireless phones in the MOBI-Kids study. Environ Int. 2022;163:107189, http://dx.doi.org/10.1016/j.envint.2022.107189.
58. Hardell L, Moskowitz JM. A critical analysis of the MOBI-Kids study of wireless phone use in childhood and adolescence and brain tumor risk. Rev Environ Health. 2022;38:409–21, http://dx.doi.org/10.1515/reveh-2022-0040.
59. Karipidis K, Mate R, Urban D, Tinker R, Wood A. 5G mobile networks and health—a state-of-the-science review of the research into low-level RF fields above 6 GHz. J Exp Sci Environ Epidemiol. 2021;31:585–605, http://dx.doi.org/10.1038/s41370-021-00297-6.