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Personal exposure to radiofrequency electromagnetic fields: A comparative analysis of international, national, and regional guidelines

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ABSTRACT

A worldwide overview and analysis for the existing limits of human exposure to Radiofrequency Electromagnetic Fields (RF-EMF) is given in this paper. These reference levels have been established by different national and even regional governments, which can be based on the guidelines provided by the recommendations of the International Commission on Non-Ionizing Radiation Protection (ICNIRP), the International Committee on Electromagnetic Safety of the Institute of Electrical and Electronics Engineers (IEEE), and even in the United States of the Federal Communications Commission (FCC), as well as, are based on the so-called precautionary principle. Explicit reference is made to the exposure limits adopted in countries or regions, such as Canada, Italy, Poland, Switzerland, China, Russia, France, and regions of Belgium (Brussels, Flanders, Wallonia), where the limits are much lower than the international standards.

The limits are compared to a selected set of in-situ measurements. This clearly shows that the measured values are typically very small compared to the international standards but could be somewhat higher compared to the reduced limits. Based on this observation and the reasonable assumption that the sensitivity of people to Electromagnetic Fields (EMF) is the same everywhere (whole-body), we propose the idea to establish a worldwide reference limit for the general public, thus applicable in all countries, if the ICNIRP considers it appropriate. Research must continue to generate measurement data that demonstrate the levels of exposure to which we are really exposed, and with this, provide arguments to the organizations that established the guidelines, especially the ICNIRP, to evaluate whether the current limits are too much. High and can be modified when considered pertinent. To the best of our knowledge, at no time has the reference level for the general public been exceeded.

1. Introduction

Due to advances in communication technologies, the general public is increasingly concerned about the appearance of possible impacts to which the population and the environment are exposed. Concerns regarding potential negative effects on health caused by RF-EMF, mainly from 100 kHz to 300 GHz, led international authorities to take decisions and establish precautionary exposure limits that are adopted by most countries, with some differences between geographic areas.

In this context, internationally respected agencies such as the International Commission on Non-Ionizing Radiation Protection (ICNIRP) (ICNIRP, 2020) and the International Committee on Electromagnetic Safety of the Institute of Electrical and Electronics Engineers (IEEE) (IEEE, 2019) have established guidelines for limiting human exposure to radiofrequency electromagnetic fields (RF-EMF) based on years of scientific research. Occupational exposure limits are crucial tools for assessing and monitoring workers' exposure to hazardous substances, whether chemical or, in our case, RF waves. They have been used for decades in all industrialized countries to prevent adverse health effects on individuals exposed to potentially harmful agents in their workplace. This concept of occupational exposure has expanded to include exposure of individuals in different environments beyond the workplace, that is, exposure to the general public has been included.

Radiological protection is governed by fundamental principles aimed

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at minimizing exposure to ionizing radiation, ensuring maximum benefits with minimal risks. These principles include the justification of exposure, optimization of protection to keep radiation doses as low as reasonably achievable, limitation of doses to prevent harmful effects, establishment of maximum permissible doses, and the use of personal dosimetry to measure and control individual radiation doses.

In the context of radiofrequency fields, a rigorous assessment is conducted to identify potential risks associated with exposure, establishing occupational and public exposure limits in accordance with guidelines from regulatory bodies such as the International Commission on Non-Ionizing Radiation Protection (ICNIRP). Adherence to regulatory norms and standards evolves with scientific and technological understanding, while ongoing scientific research addresses the complexity of long-term effects of RF field exposure.

The ICNIRP committee, through a comprehensive review of available scientific evidence, has developed criteria for different frequency ranges of the non-ionizing spectrum, particularly RF waves. Attempts were made to establish minimum exposure levels, as exceeding these minimum values could lead to adverse health effects. Once these minimum values were established, they were reduced by up to 2 % to ensure that the new minimum values could provide safety (to the extent possible) for the exposure of the general public, not just workers in their occupational setting.

As indicated, to establish these guidelines, ICNIRP identified the published scientific literature on the effects of exposure to radiofrequency electromagnetic fields on biological systems and established which of them were harmful to human health and were scientifically substantiated. The ICNIRP considers that the reported adverse effects of radiofrequency electromagnetic fields on health must be independently verified, have sufficient scientific quality and be consistent with current scientific knowledge, in order to be taken as "evidence" and to be a reference to establish exposure restrictions. As we mentioned, these committees have rigorously reviewed the evidence and provided science-based guidelines for radiological protection, which is up to the authorities of each country to adopt or not.

These guidelines are the reference limits to protect citizens from any possible harmful effects of the electromagnetic (EM) waves. The main objective of establishing a limit is to try to limit exposure to RF-EMF and achieve a high level of protection for all people against possible adverse health effects, both in the short and long term.

Some publications have commented on the controversy that arises over the limits or reference levels applied to RF-EMF personal exposure, but such approaches are different to the ones used in this application. Hinrikus et al. (2022) emphasizes thermal and non-thermal effects, and analyzes recent reviews on the effects of RF-EMF and data from RF-EMF measurements in different countries with the intention of studying possible criteria and deducing proposals for health protection limits at the level of RF-EMF under the a the light of the ALARA Principle (As Low As Reasonably Achievable).

Chou (2022) discussed the controversy in Electromagnetic Safety. The publication highlights that standards should be protective and practical to implement. Three types of standards mentioned there are: first one for the general public exposure, second one for occupational exposure and the third one regarding standards for interference with medical devices.

Dhungel et al. (2015) state that countries with higher mobile density usually set their own RF-EMF exposure limits for mobile devices and fixed installations. Foster et al. (2017) focus on the 3–10 GHz frequency range, where guidelines change for Specific Absorption Rate (SAR). Their analysis suggests that current limits may be too conservative if we really want to limit tissue temperature rise. Vijayalaxmi and Foster (2023) review the possible effects of exposure of human and animal tissues to RF-EMF waves, verifying their possible genotoxic incidence.

Gandhi, et al. (2012) indicate that many countries, especially European Union (EU) members, use the ICNIRP guidelines. His publication emphasizes that these limits are applicable to the SAR and are not really exposure limits.

Based on the analysis of publications on exposure limits, international guidelines, and exposure measurement studies, we have grouped these limits into: International guidelines, BioInitiative based on the Precautionary Principle, and National and Regional limits.

This is the motivation of this paper is to give an overview and discuss the existing limits to RF-EMF at a worldwide scale. Further, the limits are compared to actual measurements in different countries, to have a general idea of the exposure levels to which the population is subjected.

2. Eligibility criteria and published literature review

This paper combines two review methods, the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Liberati et al., 2009; Page et al., 2021a, 2021b; Panic et al., 2013) and the Population, Exposure, Comparator, and Outcome (PECO) methodology (Morgan et al., 2018), adapted to the objectives of this work about a comparative analysis of International, National, and Regional Guidelines (Fig. 1).

Following the aim of this publication related with a comparative analysis of International, National, and Regional Guidelines, to give an overview and discuss the existing limits to RF-EMF at a worldwide scale, and to compare the actual measurements in some countries, the work was carried out through a review in the Web of Science database, considering only indexed and peer-reviewed publications, that is, scientific articles published during the period 1998 to 2022 in English, and subsequently an analysis of the results. This publication is based on three phases: 1) search and review of RF-EMF related publications and guidelines. The selection criteria were as follows: Radiofrequency (Topic) AND guidelines (Title) AND exposure (Topic) AND electromagnetic field (Topic) AND 1998–2022 (Year Published) and Article or Review Article (Document Types) and English (Languages). From this search, seventeen publications were found, of which 7 were deleted, six that were not related to the objectives of the search and one that has been withdrawn.

The 10 selected publications were reviewed (Ahlbom et al., 1998; Belyaev et al., 2016; "Guidelines for Limiting Exposure to Electromagnetic Fields (100 kHz–300 GHz)," 2020; Jeschke et al., 2022; Kang and Gandhi, 2003; Li et al., 2021; Lin, 2011, 2007; Rubtsova et al., 2018; Thompson et al., 2002) and the different committees that establish and regulate the personal exposure limits to RF-EMF were identified. As well as the reference levels applied internationally (Tables 1–3, and Figs. 1–4).

2) Search and review of publications related to personal exposure measurements to RF-EM. A first search was conducted including general aspects of studies related to RF-EMF exposure measurements and 10,902 works were found. The results were so dispersed and general that we decided to carry out a second search with the following selection criteria: Radiofrequency electromagnetic fields (Topic) AND personal exposure (Topic) AND environment (Topic) AND measurements (Topic) AND mobile phone (Topic) OR base stations (Topic) AND wireless (Topic) OR Wi-Fi (Topic) AND exposure assessment (Topic) OR exposure measurement (Topic) AND personal exposimeter (Topic) AND children (Topic) AND school (Topic) AND spot measurements (Topic) OR RF-EMF (Topic) AND guidelines (Topic) AND 1998–2022 (Year Published) AND Article (Document Types) AND Web of Science Core Collection (Database) AND Physics or Research Experimental Medicine or Public Environmental Occupational Health or Life Sciences Biomedicine Other Topics (Research Areas) AND English (Languages). The total number of records found in the second search was 1701 publications.

Because some publications were not related to exposure measures and did not meet the selection criteria, and in addition, publications presenting results of RF-EMF exposure measures are found in the review articles, a third search was refined selecting only reviews. The selection criteria for the new search are: Radiofrequency electromagnetic fields (Topic) AND personal exposure (Topic) AND environment (Topic) AND

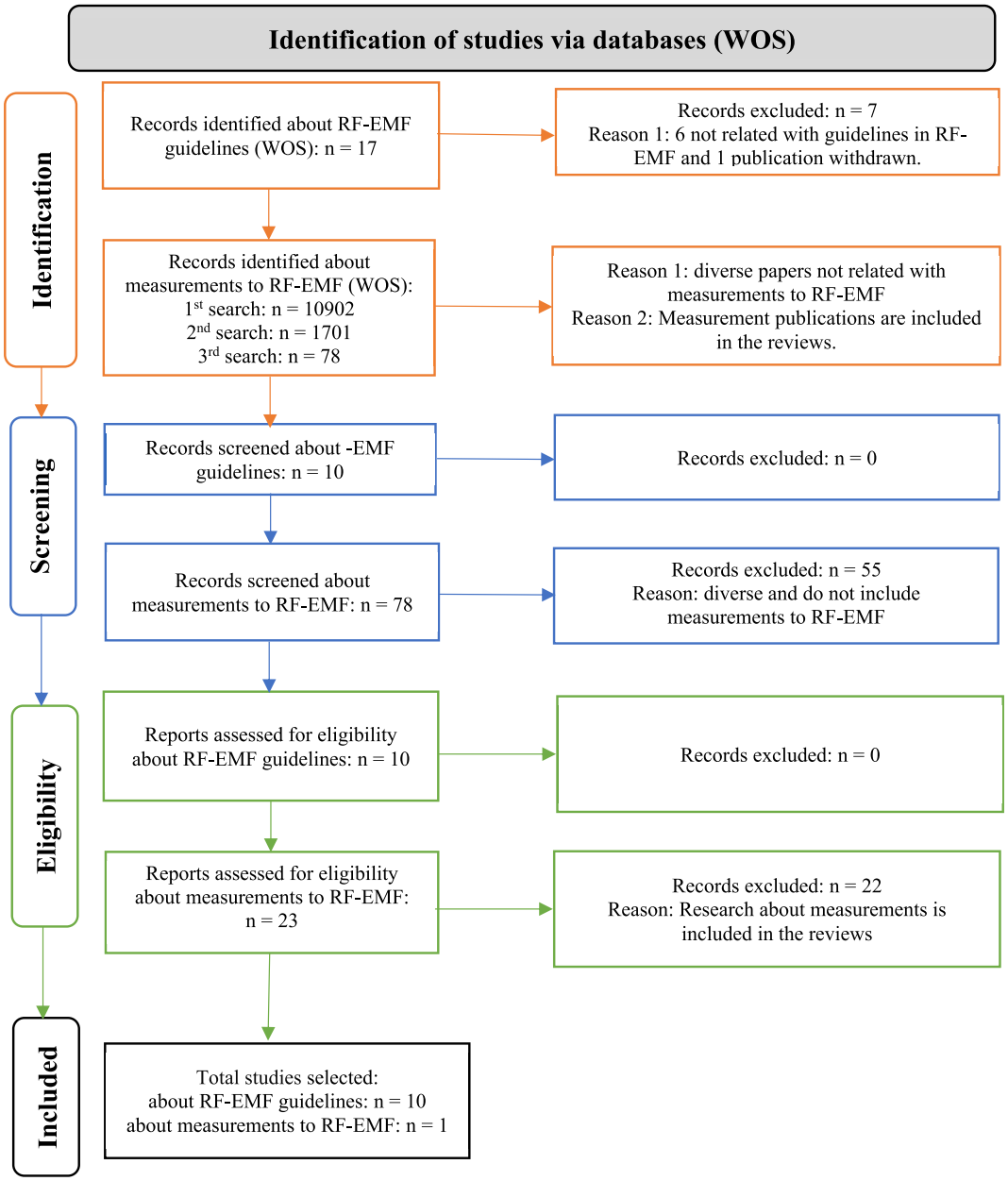

Fig. 1. PRISMA flowchart for selection and exclusion of articles: studies about RF-EMF guidelines and measurements to RF-EMF.

Table 1
International reference levels and BioInitiative Limit for exposure to RF waves, distinguishing between occupational and general public exposure.

International organization or activists	Frequency Range (GHz)	Exposure scenario	Reference level (Maximum Intensity)
ICNIRP	2–300	Occupational	50 W/m^2
		General public	10 W/m^2
IEEE		Restricted environment	50 W/m^2
		Unrestricted environment	10 W/m^2
FCC		Occupational/ Controlled Exposure	50 W/m^2
		General Population/ Uncontrolled Exposure	10 W/m^2
BioInitiative Limit	Not specified	Not given	3 μW/m^2

measurements (Topic) AND mobile phone (Topic) OR base stations (Topic) AND wireless (Topic) OR Wi-Fi (Topic) AND exposure assessment (Topic) OR exposure measurement (Topic) AND personal exposimeter (Topic) AND children (Topic) AND school (Topic) AND spot measurements (Topic) OR RF-EMF (Topic) AND 1998–2022 (Publication/Source Titles) AND guidelines (Topic) AND Article (Document Types) AND Web of Science Core Collection (Database) AND Physics or Research Experimental Medicine or Public Environmental Occupational Health or Life Sciences Biomedicine Other Topics (Research Areas) or Public Environmental Occupational Health (Research Areas) AND English (Languages) and Review Article (Document Types). Seventy-eight reviews were found, the title and abstract of said works were reviewed, it was identified that many of these works did not include research with results of measurements of personal exposure to RF-EMF, so 55 reviews were excluded, and 23 reviews were selected. The 23 review were reviewed (Adair et al., 2009; ARPANSA, 2014; Baliatsas et al., 2012; Bolte, 2016; Bosch-Capblanch et al., 2022; Chiaramello et al., 2019; Christopoulou and Karabetsos, 2015; Cucurachi et al., 2013; Dongus

Table 2
Whole-body exposures limit for RF-EMF per country/region in 2023. All data with three significant digits.

Country	Electric Field (V/m)		Intensity of the wave or Power density (W/m^2)	
	Frequency range (MHz)			
	900 MHz	1800 MHz	900 MHz	1800 MHz
Argentina	41.2	58.2	4.50	9.00
Australia	41.2	58.2	4.50	9.00
Austria	41.2	58.2	4.50	9.00
Bahrain	41.2	58.2	4.50	9.00
Belgium (Brussels)	6.00[c,d]	8.50[c,d]	0.0960[c,d]	0.192[c,d]
Belgium (Flanders)	20.6[c]/ 3.00[e]	29.0[c]/ 4.24[e]	1.13[c]/ 0.0239[e,f]	2.23[c]/ 0.0477[e,f]
Belgium (Wallonia)	3.0[e]	3.00[e]	0.0239[e,f]	0.0239[e,f]
BioInitiative	0.0336	0.0336	0.00000300	0.00000300
Brazil	41.2	58.2	4.50	9.00
Bulgaria	6.10	6.10	0.100	0.100
Canada	32.1	40.7	2.74	4.40
Chile	19.4	19.4	1.00	1.00
China	12.3·[f]	12.3·[f]	0.400	0.400
Cyprus	41.2	58.2	4.50	9.00
FCC	61.4	61.4	10.0	10.0
Finland	41.2	58.2	4.50	9.00
France	41.2	58.2	4.50	9.00
Germany	41.2	58.2	4.50	9.00
Greece	34.5	48.7	3.15	6.30
ICNIRP	41.0	58.0	4.50	9.00
IEEE	–	–	4.50	9.00
Iran	41.2	58.2	4.50	9.00
Israel	13.0	18.4	0.450	0.900
Italy	20.0/ 6.00[a]	20.0/ 6.00[a]	1.00/0.100[a]	1.00/0.100[a]
JAPAN	47.6	61.4	6.00	10.0
Malaysia	41.2	58.2	4.50	9.0
Netherlands	41.2	58.2	4.50	9.0
New Zealand	41.2	58.2	4.50	9.0
Norway	41.2	58.2	4.50	9.0
Peru	41.2	58.2	4.50	9.0
Philippines	41.2	58.2	4.50	9.0
Poland	7.00	7.00	0.100	0.100
Republic of Korea	41.2	58.2	4.50	9.00
Russian Federation	19.4·[d]	19.4·[d]	1.00	1.00
Saudi Arabia	41.2	58.2	4.50	9.00
South Africa	41.2	58.2	4.50	9.00
Sweden	41.2	58.2	4.50	9.00
Switzerland	4.00/ 41.3[b]	6.00/ 58.3[b]	0.0424/ 4.51[b,g]	0.0950/ 9.03[b,g]
Tunisia	41.2	58.2	4.50	9.00
Türkiye	10.1	14.4	0.270	0.550
UK	41.2	58.2	4.50	9.00
USA	47.6	61.4	6.00	10.0
Zambia	41.2	58.2	4.50	9.00

[a] In homes, schools, playgrounds, and places where people may stay for longer than 4 h, a value of 6 V/m is applied and averaged over any 24-h period.
[b] Installation limit value per location for new and existing antenna installations at places of sensitive use (buildings in which persons stay for longer periods).
[c] Cumulative exposure from multiple antenna locations.
[d] Maximum total field, each operator gets 33 % of the total.
[e] Per antenna in residential areas.
[f] Per antenna for frequencies between 100 kHz and 300 GHz.
[g] Own calculation.

et al., 2021; Duerrenberger et al., 2014; Foster and Moulder, 2013; Gajsek et al., 2016, 2015; Galli et al., 2019; Inyang et al., 2008; Jalilian et al., 2019; Khurana et al., 2010; Moulder et al., 2005; Pophof et al., 2021; Ramirez-Vazquez et al., 2023b; Repacholi et al., 2012; Röösli et al., 2010, 2010), and finally, the recently published review (Ramirez-Vazquez et al., 2023b) was selected, which includes the publications of the previous review articles (Fig. 1).

Table 3
Local and regional exposure limits for Flanders and Brussels[a,b,c] (Brussels Capital Region, 2013; Flemish Region, 2010; Velghe et al., 2019). The limits are expressed in W/m^2. All data with three significant digits.

Local regulations Frequency	Range (MHz)	Flanders (W/m^2)		Brussels (W/m^2)
		Cumulative	Per antenna (indoor)	Cumulative
(Brussels Capital Region, 2013; Flemish Region, 2010)	10–400	0.498	0.0110	0.0430
	400–2000	0.00120·f	0.0000270·f	0.000107·f
	2000–10 000	2.50	0.0532	0.220

[a] f is the frequency in MHz.
[b] Cumulative data represent the regulatory exposure limit per base station. Flanders has an extra limitation per antenna for indoor places and children and school playgrounds: 0.0106 W/m^2 between 10 and 400 MHz, 0.0000270·f W/m^2 between 400 and 2000 MHz, 0.0532 W/m^2 between 2 and 10 GHz.
[c] In both legislations, there is also a cumulative limit across frequencies for all sources: $\sum S_i/S_{limit,i} \leq 1$ with S_i (W/m^2) the measured power density at frequency i and $S_{limit,i}$ (W/m^2) the limit value (as shown in the table above).

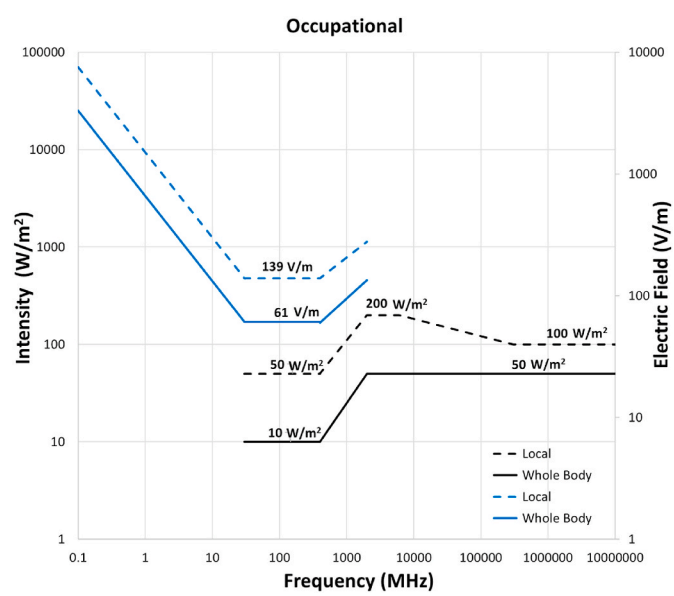

Fig. 2. Reference levels for local and whole-body exposures in the occupational scenario. Intensity is given black and whereas Electric Field in blue. Elaboration based on the ICNIRP guidelines (ICNIRP, 2020).

Considering the results presented in the recently published review (Ramirez-Vazquez et al., 2023b), an analysis was conducted and two tables were prepared that summarize the results. The selection criteria for the research included in these tables (Tables 4 and 5) were chosen by applying the PECO methodology; the eligibility criteria are indicated before the aforementioned tables appear.

3) Finally, considering the reference levels established by international organizations and adopted by most countries, as well as the national and regional limits established in some countries or those established by activist groups, and taking into account the results of the research on exposure measures, a comparative analysis was carried out and thus meet the objective of this publication.

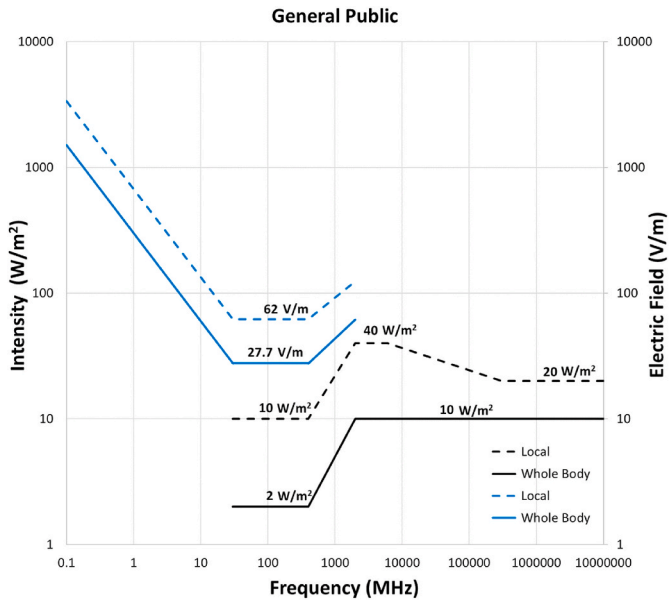

Fig. 3. Reference levels for local and whole-body exposures in the General public scenario. Intensity is given black, whereas Electric Field in blue. Elaboration based on the ICNIRP guidelines (ICNIRP, 2020).

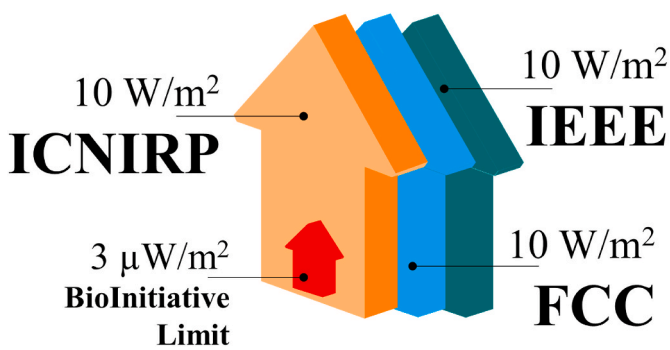

Fig. 4. ICNIRP (ICNIRP, 2020), IEEE (IEEE, 2019), FCC (FCC, 2019, 1997) and BioInitiative Limit (BioInitiative Report, 2012) reference levels for the general public. The figure is not made to scale. Frequency Range 2–300 GHz.

3. Exposure limits

3.1. International guidelines

ICNIRP has established international exposure limits that are adopted by numerous countries around the world. The exposure limits of IEEE and the FCC are also taken into account when making decisions, as they are highly trusted organizations. Obviously, the FCC has greater influence in its area, the United States. The ICNIRP defines the maximum reference levels between 2 and 300 GHz for two exposure scenarios: 50 W/m^2 for Occupational exposure and 10 W/m^2 for the General public (ICNIRP, 2020), see Figs. 2 and 3. These limits are consistent with the limits set by the IEEE and the Federal Communications Commission (U.S. government agency) (FCC, 2019, 1997), being 50 W/m^2 for Restricted or Controlled environment and 10 W/m^2 for Unrestricted or Uncontrolled environment.

The World Health Organization (WHO) (WHO, 2017), the Federal Communications Commission (FCC) (FCC, 2020), and the International Telecommunications Union (ITU) (ITU, 2022), as well as the European Council (EC, 1999) have used these principles to make information repositories so that the governments of countries that wish to do so can use all known science to achieve the greatest well-being of citizens. A lot of

Table 4
Personal exposure to RF-EMF in Wi-Fi bands in schools and universities (indoor classroom or outside environment) in different countries. All data with three significant digits. The data have been ordered from lower to higher exposure. The four values that do not exceed the BioInitiative Limit have been highlighted.

Country/ microenvironment	Source	Electric Field (V/m)	Intensity of electromagnetic wave (μW/m^2)
Palestine/inside school	WLAN band	0.00500[a]	0.0600[a]
Palestine/inside universities area	WLAN band	0.00800[a]	0.180[a]
Turkey/inside classroom	WLAN band	0.0220[a]	1.28[a]
Spain/inside university	Wi-Fi band	0.0310[a]	2.55[a]
Switzerland/at school	Wi-Fi band using WLAN band	0.0351[a]	3.27[a]
Sweden/schools	Wi-Fi band	0.0354[a]	3.32[a]
Belgium/school area	Wi-Fi band	0.0500[a]	6.64[a]
Greece/school area	Wi-Fi band	0.0635[a]	10.7[a]
Kosovo/school area	Wi-Fi band	0.0835[a]	18.5[a]
Greece/school area	2G Wi-Fi band	0.0898 [a]	21.4[a]
Jordanian/total exposure around university area	Wi-Fi band (2G and 5G bands)	0.0931[a]	23.0[a]
Spain/school building	Wi-Fi band (2G and 5G bands)	0.0977[a]	25.3[a]
Jordanian/university area	Wi-Fi band (2G and 5G bands)	0.104[a]	28.8[a]
Sweden/in seven schools	Wi-Fi band connection	0.158[a]	66.1[a]
Kosovo/at university (different offices)	Wi-Fi band	0.163[a]	70.2[a]
Australia/kindergarten area	Wi-Fi band	0.179[a]	85.0[a]
Belgium/school area	Wi-Fi band	0.200[a]	106[a]
Spain/inside classroom	diverse sources including Wi-Fi band	0.213[a]	120[a]
Belgium (10 school area)	various Wi-Fi devices[a,b]	0.0500[a], 0.240[b]	6.63[a], 153[b]
Greece (5 school area)	various Wi-Fi devices[a,b]	0.0900[a], 0.200[b]	21.5[a], 106[b]
Belgium/5 primary and secondary schools	access points various Wi-Fi clients[a,b]	0.340[a], 2.52[b]	307[a], 16,800[b]
Croatia/151 primary & secondary schools	access points[a,b]/ across whole classroom (grid 1 × 1 m)	<0.661[b]	<1160 [b]
New Zealand/2 schools	access points[b]/2 laptops/<0.5	0.971[a], 2.746[b] 0.868[a], 3.36[b]	2500[a], 20000[b] 2000[a], 30,000[b]
Australia/7 primary 16 secondary schools	access points[c,d]/ 1.9	0.388[a], 3.88[b]	400[a], 40,000[b]
United Kingdom/3 primary and 3 secondary schools	Laptops/0.5	2.90[b]	22,300[b]
Hungary/31 primary school teacher	Wi-Fi devices[a]	2.00–5.00[a]	10,600–66300[a]
United Kingdom/3 primary and 3 secondary schools	access points[a]/ 0.5	5.70[b]	86,200[c]
Relevant ICNIRP reference levels[e]		**61 V/m**	**10 W/m^2**
Limit proposed by the BioInitiative		**0.0336 V/m**	**3 μW/m^2**

Note that all measurements in Table 4, except the four bold and highlighted ones, surpass the BioInitiative Limit proposed by the (BioInitiative Report, 2012).

[a] 2.4–2.5 GHz.
[b] 5.15–5.85 GHz.
[c] Average value.
[d] Maximum value.
[e] Reference levels for general public exposure to time-varying electric and magnetic fields: electric field strength and equivalent plane wave power density refer to the 2–300 GHz frequency range (ICNIRP, 2020).

Table 5
Results of some studies below 3 μW/m^2 (Ramirez-Vazquez et al., 2023b). All data with three significant digits.

Country/ microenvironment	Source	Electric Field (V/m)	Intensity of electromagnetic wave (μW/m^2)
Egypt/Shebin El-Kom City (Menoufiya governorate)	Total exposure from MBPSs	0.000614[a]	0.00100[a]
Switzerland/Zurich	UMTS UL	0.00152[c]	0.00610[c]
Belgium	Wi-Fi 5G	0.00388[c]	0.0400[c]
France/Lyon	Wi-Fi band	0.00476[c]	0.0600[c]
France/Lyon	Wi-Fi 2G	0.00476[d]	0.0600[d]
France/Lyon	Wi-Fi 5G	0.00476[d]	0.0600[d]
Australia and Belgium/in a car	Mobile phone base stations	0.00700[c]	0.130[c]
Denmark, the Netherlands, Slovenia, Switzerland, and Spain/in home	DECT	0.00868[c]	0.200[c]
Spain/Albacete	DCS	0.00990[c]	0.260[c]
France/Lyon	Wi-Fi 5G	0.0100[a]	0.266[a]
France/Lyon	Wi-Fi 2G	0.0110[a]	0.320[a]
Egypt/Shebin El-Kom City (Menoufiya governorate)	Total exposure from MBPSs	0.0123[a]	0.400[a]
Australia/Melbourne	Total Wi-Fi 2.4 GHz	0.0160[d]	0.680[d]
Switzerland/Central Switzerland	DECT	0.0194[c]	1.00[c]
Spain/Albacete	GSM, UMTS and DECT	0.0200[c]	1.06[c]
Spain/Albacete	GSM, UMTS and DECT	0.0200[c]	1.06[c]
Denmark, the Netherlands, Slovenia, Switzerland, and Spain/in home	Wi-Fi	0.0203[a]	1.09[a]
Netherlands/Amsterdam and surroundings/on a bike in the city center area	Wi-Fi and WLAN band	0.0211[a]	1.18[a]
Australia/Melbourne	900 MHz downlink band	0.0220[d]	1.28[d]
Australia/Melbourne/ higher education and research sector and office workers	Wi-Fi	0.0221[d]	1.30[d]
Australia/Melbourne	Wi-Fi 2.4 GHz	0.0230[d]	1.40[d]
Australia/Melbourne/ higher education and research sector and office workers	Wi-Fi	0.0234[d]	1.45[d]
Belgium	Wi-Fi 5G	0.0238[b]	1.50[b]
Australia/Melbourne/ higher education and research sector and office workers	Wi-Fi	0.0240[d]	1.53[d]
South Korea/Seoul, Cheonan, and Ulsan/in home	Wi-Fi	0.0252[c]	1.68[c]
Australia/Melbourne/ higher education and research sector and office workers	Wi-Fi	0.0253[d]	1.70[d]
Switzerland/Central Switzerland	all frequency bands	0.0259[c]	1.78[c]
Denmark, the Netherlands, Slovenia, Switzerland, and Spain/in home	Wi-Fi	0.0260[d]	1.80[d]
Denmark, the Netherlands, Slovenia, Switzerland, and Spain/in home	DECT	0.0266[a]	1.88[a]
Austria/Vienna and Carinthia/in urban area	Total exposure from MBPSs	0.0275[a]	2.00[a]
South Korea/Seoul, Cheonan, and Ulsan/in home	Downlink	0.0281[b]	2.10[b]
Germany/Munich, Freising, Ebersberg and Grafing	Total exposure from WLAN	0.0283[a]	2.12[a]
Netherlands/Amsterdam and surroundings/on a bike in the city center area	UMTS Downlink	0.0283[c]	2.12[c]
South Korea/Seoul, Cheonan, and Ulsan/in home	Wi-Fi	0.0307[a]	2.50[a]
Spain/Albacete	Wi-Fi 5G	0.0323[a]	2.77[a]
Belgium/Ghent	900-DL	0.0328[c]	2.85[c]
Relevant ICNIRP reference levels[e]		**61 V/m**	**10 W/m^2**
Relevant ICNIRP reference levels (900 MHz)		**41**	**4.5**
Relevant ICNIRP reference levels (1800 MHz)		**58**	**9**
Limit proposed by precautionary principle		**0.0336 V/m**	**3 μW/m^2**

[a] Average value.
[b] Maximum value.
[c] Minimum value.
[d] Median value.
[e] Reference levels for general public exposure to time-varying electric and magnetic fields: electric field strength and equivalent plane wave power density refer to the 2–300 GHz frequency range (ICNIRP, 2020).

countries have adopted these scientifically based RF-EMF guidelines. However, some countries such as Canada, Italy, Poland, Switzerland, China, Russia, and Belgium have established even stricter limits (Aerts et al., 2019; ITU-T, 2019; Madjar, 2016; Urbinello et al., 2014; Velghe et al., 2019). These limits will be discussed later.

3.2. BioInitiative guidelines

In a recently published article by Chou (2022) it is clearly pointed out that there are groups of activists who are continuously questioning the reference levels established by the ICNIRP (2020), IEEE (2019), and FCC (1997, 2019). They claim to promote the precautionary principle, which, according to them, demands lower maximum exposure limits. Ten years ago, in the BioInitiative Report (2012) these activist groups proposed an exposure limit of 0.3 nW/cm^2 which is much lower (six orders of magnitude) than the generally accepted limits.

From our point of view, the limit called "Precautionary Principle" by the BioInitiative (BioInitiative Report, 2012) is misleading and a strategic mistake, since there is also a level of precaution in the other limits. In this work, we will call this limit the "BioInitiative Limit", and it can be expressed following Ramirez-Vazquez et al. (2022) as 3 μW/m^2, see Fig. 4.

Table 1 shows the reference levels (or maximum permitted exposure values) established by ICNIRP (2020), IEEE (2019), FCC (FCC, 2019, 1997) and by the BioInitiative (BioInitiative Report, 2012).

ICNIRP's published guidelines (ICNIRP, 2020) limit exposure to electromagnetic fields (100 kHz–300 GHz), updating its previous guidelines (ICNIRP, 1998). The restrictions specified in these guidelines provide protection against potential adverse health effects from exposure to new RF-EMF technologies.

ICNIRP in 2020 introduces two new restrictions with the intention of strengthening the protection of people's health: 1) Related to the development of technologies that use frequencies higher than 6 GHz, such as the new 5G, to better protect against excessive increase temperature in the body. 2) Deal with brief exposures (less than 6 min) to

ensure that a temporary increase in temperature cannot negatively affect the tissue, for the whole-body. Throughout this work, we will consider the exposure over the whole-body and, if at any time the exposure is local, we will comment on it.

ICNIRP (1998) set a restriction on the Specific Energy Absorption Rate (SAR) quantity. ICNIRP (2020) also did so but extended the 10 GHz to a new range of 100 kHz–300 GHz. The goal of this change is to try to ensure that exposure to new technologies does not cause an excessive increase in body temperature. The average time also changed from the initial 6 min–30 min. The above deals with the SAR limits, however the values of the basic guidelines have not changed, as there are numerous publications indicating that they were even more conservative than initially thought. Hirata and Kodera (2020) focused their work on aspects related to the new 5G technology.

3.3. National and regional guidelines

Due to the continuing concern about RF-EMF, limits have been established in countries, regions or even cities within the same country, in a way that they are 10–100 times lower than the international reference levels (ITU-T, 2019; SCENIHR, 2015; Velghe et al., 2019; WHO, 2017). This is especially the case in Europe, i.e., in Poland, Russia, Italy, Switzerland, France, and regions of Belgium (Brussels Capital Region and Flanders Region). In general, Northern Europe, more aligned with 1999/519/EC than Southern Europe, and there are no clear distinctions between Western and Eastern European countries (EC, 1999; Madjar, 2016).

It also has to be pointed out that, in addition to the exposure limits for telecom base stations (BS) and transmitters (Tx), the exposure due to, i.e., mobile phones themselves in the 100 kHz to 300 GHz band have been regulated by national organizations such as the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) (ARPANSA, 2014, 2015), the American National Standards Institute (ANSI) (ANSI/IEEE, 2002), the European Committee for Standardization (CEN), and the European Committee for Electrotechnical Standardization (CENELEC) (CENELEC, 2021).

Note that in this work, the terms intensity I of the EM wave and power density are considered fully equivalent. Therefore, the exposure levels are expressed in W/m^2. Some authors express exposure levels to RF-EMF in V/m. This means that the electric field is considered instead of the intensity. The relation between them is $I = E^2/377$ as adopted in (Ramirez-Vazquez et al., 2022). Where needed, the conversion of the values in V/m to values in W/m^2 or μW/m^2, or vice versa, was performed (Ramirez-Vazquez et al., 2022).

Table 2 gives the exposure limit values for the wide range of countries and regions that has been considered. Note that in Canada, Italy, Switzerland, China, Poland, Russia, France and Belgium (Brussels Capital Region and Flanders Region) (Brussels Capital Region, 2013; Flemish Region, 2010; Madjar, 2016; Velghe et al., 2019; WHO, 2017), the limits are much stricter than elsewhere. This table presents the limits different from those established by the ICNIRP, which are more restrictive and belong to the 900 and 1800 MHz bands, which are the most used frequencies.

Table 3 shows the local and regional exposure limits in Flanders and Brussels, which have been used by Velghe in 2019 (Velghe et al., 2019) to compare measured exposures in different microenvironments in Flanders, Belgium.

As we can see in Tables 2 and 3, there are considerable differences in the exposure limits between different European countries. Belgium is a special case, due to its complex political situation. Different limits apply in the Brussels, Flemish and Wallonish regions (Brussels Capital Region, 2013; Flemish Region, 2010; Velghe et al., 2019; WHO, 2017).

3.4. General overview

As we have seen previously, there are different exposure limits in which the reference levels established by the ICNIRP prevail. The most countries apply the exposure limits established by ICNIRP (ICNIRP, 2020). However, some countries (Figs. 5 and 6) adopt stricter limits (ITU-T, 2019; WHO, 2017), and this is the reason why we have mentioned them in this study.

Figs. 5 and 6 show the different exposure limits, ordered from higher to lower, including the international limit established by the ICNIRP, and including the most restrictive limits adopted by some countries, cities, or regions. Fig. 5 shows the limits for the 900 MHz band and Fig. 6 those for the 1800 MHz band.

In addition, in this work we would also like to highlight the GSMA website, which gives us the option of viewing in a very general way the countries that apply the exposure limits established by international organizations through a map (GSMA, 2021).

With this work, we intend to analyze and discuss the existing RF-EMF limits, compare them with results of measurements carried out in some countries, and based on the results, make a proposal aimed at the unification of presented limits, thus avoiding confusion and possible controversies.

4. Overview and analysis of measurements

In this section, we show an overview of some measurements carried out in several countries, mostly in Europe, within educational centers. This allows us to handle data that is relatively homogeneous and at the same time provide us with information about personal exposure in these micro-environments in which children, young people and professors spend a significant amount of time, such places can be seen as "sensitive centers" (Table 4). In this first table of measurement results, we have included works focused on measurements carried out in the Wi-Fi band, a table that we have recently published (Arribas et al., 2022). Subsequently, we comment some measurements carried out in a Spanish university (Ramirez-Vazquez et al., 2023a), and in Table 5 we present the results of personal exposure measurements carried out in different microenvironments, obtained from a recently published review (Ramirez-Vazquez et al., 2023b).

The long-lasting concern about RF-EMF in many countries has led to the measurement of exposure, spectrum analyzers (SA) and dedicated exposimeters, in different environments and situations. In particular, Table 4 shows measurements carried out in schools and universities (indoor/classroom or outside environment) in two Wi-Fi frequency bands in different countries (Arribas et al., 2022). These countries have been selected because they have made measurements of wireless connections in buildings dedicated to education. Considering the PECO methodology, the selection criteria are Population: intensity of Wi-Fi in public buildings; Exposure: RF-EMF, exposure measurement in schools and universities, students, and professors' exposure; Comparator: RF-EMF exposure, inside and outside exposure; Outcome: studies that present statistical results about RF-EMF exposure levels.

A recent study (Ramirez-Vazquez et al., 2023a) shows results of the exposure levels in the 2.4 GHz and 5.85 GHz Wi-Fi band measured in three years, inside the building of the Faculty of Computer Science Engineering of the University of Castilla-La Mancha, in Albacete, Spain. The faculty is a building with many computers, cell phones and various Wi-Fi networks to serve approximately 800 students and 150 professors.

The exposure levels in the entire building is within the limits established by the ICNIRP and the IEEE (ICNIRP, 2020; IEEE, 2019). And if we compare the results recorded by Ramirez-Vazquez et al., many values would be in the non-allowed range according to the BioInitiative Limit, these maps can be consulted in the publication (Ramirez-Vazquez et al., 2023a). Of all the measurements carried out around the building (Ramirez-Vazquez et al., 2023a) only four values are below 3 μW/m^2, and only the middle area of the building would comply with this limit.

If the BioInitiative limit were to be adopted, the Wi-Fi service would have to be suspended in most of the building. Similarly, this proposed limit would be breached in the measurements carried out in a classroom

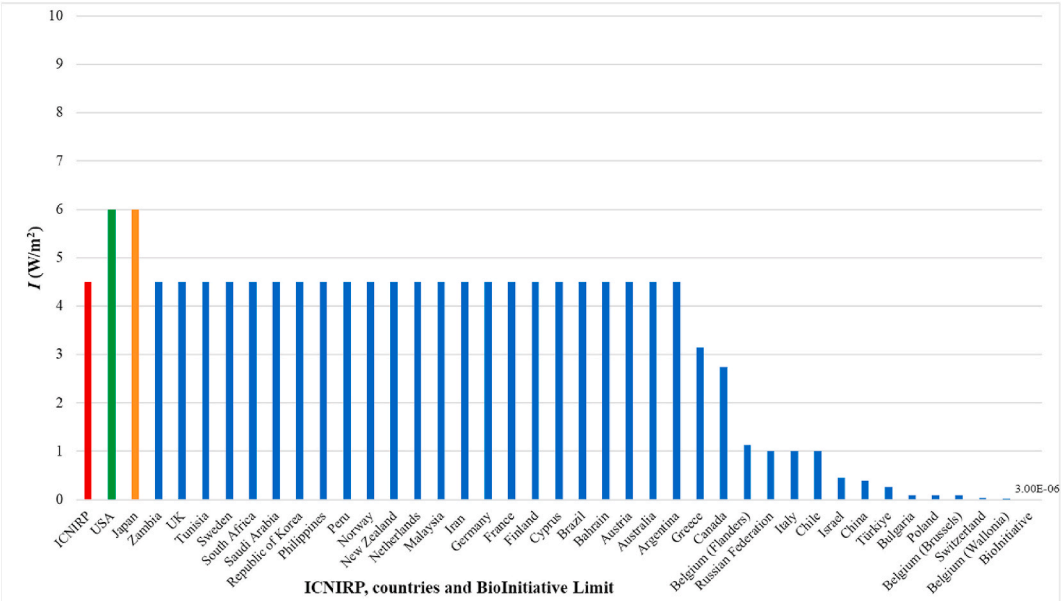

Fig. 5. Exposure limits to RF-EMF for General Public by country in the 900 MHz band in 2023, including international reference and BioInitiative Limit.

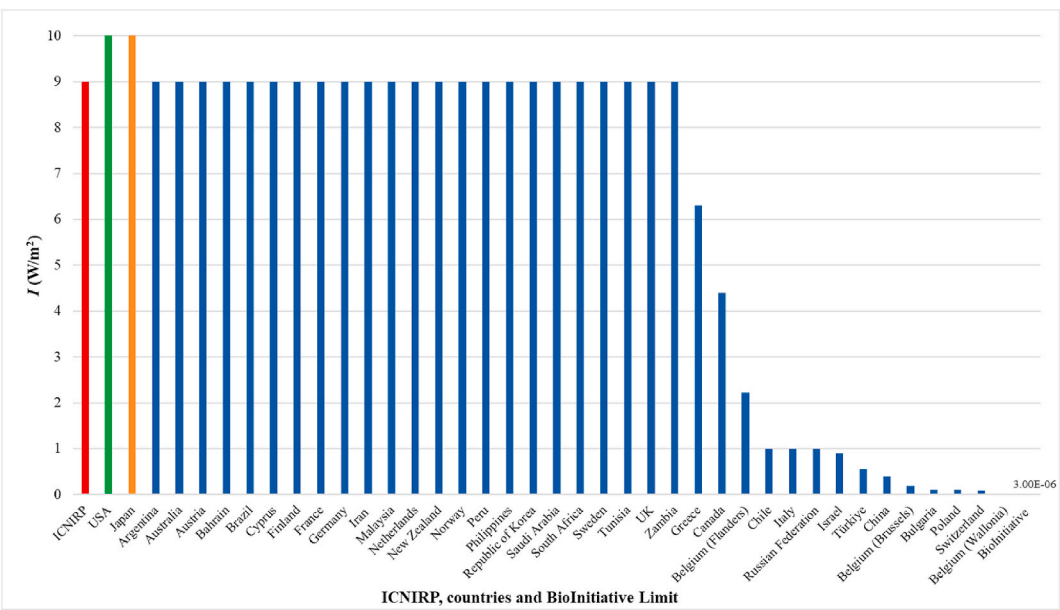

Fig. 6. Exposure limits to RF-EMF for General Public by country in the 1800 MHz band in 2023, including international reference and BioInitiative Limit.

with and without students, and inside a professor's office (Ramirez-Vazquez et al., 2023a).

In Table 4 we see that the measurements carried out in a university center, focusing on the Wi-Fi band, show values that are very small and considerably below the international reference limits, even below the more restrictive limits adopted by some countries, such as the case of Belgium (4.24 V/m equivalent to 0.0239 W/m^2). However, if we consider the BioInitiative Limit (0.0336 V/m equivalent to 3 μW/m^2) only six values would comply with said limit. Therefore, this very restrictive limit does not reflect scientific point of view. It would seriously compromise connectivity, and all the advantages linked to it. BioInitiative is a non-governmental organization, but it has a great influence on certain highly aware sectors of the population.

Considering different microenvironments, a review has recently been published by (Ramirez-Vazquez et al., 2023b) on personal measurements with volunteers and with a trained researcher in different RF bands. In that work, 56 publications in different countries and microenvironments were analyzed. Only in a third of them (19 studies) the value proposed by the BioInitiative would have been met, considering cases from different countries: Austria, Egypt, Germany, Switzerland, Australia, Denmark, the Netherlands, Slovenia, South Korea, France, Spain and Belgium. In most countries values are above this limit (Ramirez-Vazquez et al., 2023b).

In Table 5 we present the results from our recent review (Ramirez-Vazquez et al., 2023b) that have values below 3 μW/m^2, being the most restrictive exposure limit (BioInitiative Limit), as already stated. According to the PECO methodology the selection criteria are Population: RF-EMF in different microenvironments; Exposure: exposure measurement from different sources, Mobile phone base stations (MBPSs) and Wi-Fi; Comparator: intensity levels below 3 μW/m^2; Outcome: results of RF-EMF exposure levels below 3 μW/m^2.

To the best of our knowledge, the intensity levels of RF-EMF

measured during last couple of years do not exceed neither 61 V/m (10 W/m^2) (ICNIRP reference levels) nor 3 V/m (0.0239 W/m^2) and 4.24 V/m (0.0477 W/m^2) applied in Belgium, being very restrictive. According to (Hinrikus et al., 2022; Ramirez-Vazquez et al., 2023a), the levels are even decreasing with the arrival of new generations of telecommunication technology.

The data in this table comply with the BioInitiative. However, 66 % of the studies presented in the review do not comply (Ramirez-Vazquez et al., 2023b).

5. Discussion

The ICNIRP is an independent expert scientific commission that provides scientific advice and guidance on the health and environmental effects of Non-Ionizing Radiation (NIR) to protect people and the environment. It works with the WHO and other government agencies. Another international body that sets exposure limits in accordance with ICNIRP is the IEEE. Most of the countries adopt these international limits. However, due to the population's concern about the possible hazardous effects of RF-EMF, some countries establish more restrictive limits. Groups of activists even propose limits that, according to state-of-the-art measurements, would compromise the proper functioning of the existing networks, such as the BioInitiative. For example, inside buildings, the rooms furthest away from the modem would lose Wi-Fi coverage. Also, signals coming from mobile phones are greatly attenuated inside houses, so that with this limit mobile phone coverage would be seriously at risk. In that sense the limit proposed by the BioInitiative (3 μW/m^2) is really too low, especially further considering the fact that scientific evidence in favor of this limit is weak.

Another important reason for the fact that exposure limits differ substantially in different countries is the vulnerability of political intervention and activist pressure in these national decisions. The case of Belgium is a perfect example of this, having three different regulations in even smaller regions (Brussels, Flanders, Wallonia). National and regional exposure limits established internally have no scientific basis; these countries/regions have decided to weigh other aspects in addition to scientifically established health effects when establishing their guidelines, such as concern in the general population.

The measurements performed in different countries and cities, and in various microenvironments demonstrated that the level of RF-EMF does not exceed the level of 10 W/m^2 established by ICNIRP reference levels. The maximum level informed in a recent review was 285,000 μW/m^2 (0.285 W/m^2), i.e. 15 dB below the maximum allowed of 10 W/m^2 (Ramirez-Vazquez et al., 2023b).

We want to highlight that new technologies employ lower RF-EMF levels. The new devices become more and more efficient, for example by employing shorter time intervals, in this way requiring less energy to provide high quality and speed of data transmission. We can verify this in the recently published results, where measurements were made over three consecutive years. We clearly observe that in the 2.4 GHz Wi-Fi band the average was 6.36 μW/m^2 in 2017 and 3.02 μW/m^2 in 2019, whereas in the 5.85 GHz Wi-Fi band the average was 30.5 μW/m^2 in 2017 and 15.7 μW/m^2 in 2019. Consequently, the level of RF-EMF has been significantly reduced, and therefore also the consequent possible health risk (Ramirez-Vazquez et al., 2023a).

6. Conclusion

The duality of limits in the same country does not seem appropriate, because people who live in one area or another have more or less the same interaction with RF-EMF waves. Therefore, the limits should be the same, following the ALARA principle – As Low As Reasonably Achievable. The reasons for setting the maximum exposure limit should only be scientific related, not political or in any other way.

In this paper, we provided an overview, analyze, and discuss existing limits to RF-EMF. The international reference levels established by ICNIRP are also recommended by WHO, IEEE and FCC, and are adopted by most countries. However, some countries such as Canada, Italy, Poland, Switzerland, China, Russia, France, and regions of Belgium establish more restrictive limits than the international ones. The case of Belgium is rather specific because it establishes three very strict and different limits in Brussels, Flanders, and Wallonia.

In addition to the international limits, we have commented on the BioInitiative Limit, based on the Precautionary Principle as a preventive action, an excessively restrictive value that leaves aside more than 60 % of the personal exposure studies to RF-EMF.

There should be a trend towards unifying the limits of exposure to RF-EMF in all countries. This would allow decisions to be made in a scientific and consensual manner. The solutions could follow the ones from the International Union for Pure and Applied Physics (IUPAP), which is an international organization that has sixty member countries and is in charge, among other things, of the correct use of the International System of Units and of reviewing the measurement units of the physical magnitudes.

Based on the observation and analysis of measured levels that in most cases, the measured levels are very small, we propose that a reference limit be established for the general public, reasonable and applied to all countries, if the ICNIRP considers it appropriate. Therefore, research must continue to generate measurement data that demonstrate the levels of exposure to which we are really exposed, and with this, provide arguments to the organizations that established the guidelines, especially the ICNIRP, so that they evaluate whether the current limits are too high and can be modified, when considered pertinent. To the best of our knowledge, at no time has the reference level been exceeded for the general public, and we believe that it will not be exceeded, since the new smartphones require much less intensity than previous models, and the same goes for new technologies, 5G, 6G.

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CRediT authorship contribution statement

Raquel Ramirez-Vazquez: Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Isabel Escobar:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Guy A.E. Vandenbosch:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Enrique Arribas:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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