LIMITS OF EXPOSURE TO ELECTROMAGNETIC FIELDS – A REVIEW OF STANDARDS AND REGULATIONS

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Abstract: *Identification of risks and potential effects of exposure to electromagnetic fields has aroused the interest of researchers in various fields to reduce or even eliminate them. However, the problems they raise, also, determined the need to regulate the exposure limits, thus establishing a series of regulations at the level of different states, of some national and international standards. The paper presents a comparative analysis of several national and international regulations regarding the exposure limits for the general public and for different working environments.*

1. INTRODUCTION

Multiple uses of electricity make it essential for modern everyday life. But, over time, in addition to the undeniable positive effects, various forms of negative impact on humans and the environment have been observed and identified.

Identification of risks and potential effects of exposure to electromagnetic fields has aroused the interest of researchers in various fields to reduce or even eliminate them. However, the problems they raise, also, determined the need to regulate the exposure limits, thus establishing a series of regulations at the level of different states, of some national and international standards.

The paper presents a comparative analysis of several national and international regulations regarding the exposure limits for the general public and for different working environments. The methodology of this study consists in different methods, mainly literature review, data analysis, classification and problem identification.

2. EVOLUTION OF REGULATION ON LIMITING EXPOSURE TO ELECTROMAGNETIC FIELDS

In order to prepare a regulation or a guideline for limiting exposure, different national or international organizations involved in such activities make an extensive review of relevant literature on health and biological effects.

According to Directive 2013/35/EU, effects of electromagnetic fields on human body are direct biophysical effects and indirect effects. The first category includes non-thermal effects, thermal effects and limb currents [1]. Non-thermal effects, associated with different frequency and intensity, are vertigo, nausea (static magnetic fields), effects on sense organs (up to 100 kHz), effects on nerves, muscles (up to 10 MHz). Thermal effects in the form of heating is present also for intermediate frequencies (100 kHz – 10 MHz) and for high frequency fields (10 MHz and above). These effects are identified based on epidemiological, occupational, laboratory, volunteer, cellular and animal studies.

Among the causes of the increase in environmental EMF levels presented by the World Health Organization are high voltage transmission lines, telecommunication and broadcast transmitters, radars, transportation systems and undersea power cables [2].

First countries that introduced regulations on limiting exposure to electromagnetic fields against adverse effect on workers and public were the former Soviet Union USSR and USA. The first standard developed and published in 1958 by the former Soviet Union regulated the limitation of RF exposure of workers [3]. In 1960, the American Standards Association approved the Radiation Hazards Standards project under the co-sponsorship of the Department of the Navy and the Institute of Electrical and Electronics Engineers [4].

In the following period, the number of countries concerned with this issue grew, conducting numerous studies on the effects and risks generated by exposure to electromagnetic fields. Over time, more and more organizations, globally, have addressed the issue of limiting exposure to the undesirable effects of electromagnetic fields (see Table 1).

In 1974, International Radiation Protection Association IRPA formed a working group that analysed the problem of protection against non-ionizing radiation NIR [5] and in 1977, this group became the International Non-Ionizing Radiation Committee INIRC. This organization, in cooperation with Environmental Health Division of WHO developed a series of health criteria documents on NIR.

In 1992, it became International Commission Non-Ionizing Radiation Protection ICNIRP and in 1998 released Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 300 GHz).

Starting from this moment a series of regulations, guidelines, recommendations and other documents were issued by national or international bodies, as the number of studies on

the effects of electromagnetic fields has increased, but also due to the growing public interest in the problems generated by the presence of electromagnetic fields (see Table 2).

Table 1. International organisations involved in research or regulation of exposure to electromagnetic fields

Organisation	Short description
IEC International Electrotechnical Commission	worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees)
ICOH International Commission on Occupational Health	international non-governmental professional society - fosters the scientific progress, knowledge and development of occupational health and safety
CIE International Commission on Illumination	independent, non-profit professional organization, authority on the subject matter of light and lighting
ILO International Labour Organization	U.N. agency, sets labour standards, develops policies and devises programmes promoting decent work for all women and men
ACGIH American Conference of Governmental and Industrial Hygienists	charitable scientific organization that advances occupational and environmental health
ISO International Standards Organization	independent, non-governmental international standard-setting body composed of representatives from national standards organizations
WHO World Health Organization	organization that promotes health, keeps the world safe, and serves the vulnerable.
IEEE Institute of Electrical and Electronic Engineers	technical professional organization designed to serve professionals involved in all aspects of the electrical, electronic, and computing fields and related areas of science and technology
IRPA International Radiation Protection Association	association of radiation protection professionals joining through national and regional radiation protection societies
European COST Cooperation in the Field of Science and Technology	funding organisation for the creation of research networks
CENELEC European Committee on Electrotechnical Standardisation	responsible for standardization in the electrotechnical engineering field
ICNIRP International Commission on Non-Ionizing Radiation Protection	independent group of experts established to evaluate the state of knowledge about the effects of NIR on human health and well being

In the same time, since 1998, WHO has started a project to harmonize EMF standards worldwide, involving 8 international organizations and over 45 countries, starting from the fact that there were large differences between the existing standards at that time, in some cases there were even differences of two orders of size [2].

Regarding the ICNIRP Guidelines, this document distinguished between occupational and general exposure limitations, introducing significantly different values for these types of exposure, justified by the following considerations:

- general public includes persons of different ages, health conditions,
- many members of that are unaware of their exposure to EMF and potential risks,
- no expectations can be raised regarding the adoption by the general public of reasonable measures to minimize or avoid exposure.

Table 2. Regulations, recommendations, guidelines, and other documents related to exposure to electromagnetic fields

Year	Regulation / Document	Regulatory body	Domain / description
1998	Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields	ICNIRP	Establishes guidelines for limiting EMF exposure that will provide protection against known adverse health effects.
1999	Council Recommendation 1999/519/EC on the limitation of exposure of the general public to electromagnetic fields (0 Hz to 300 GHz)	EC	Recommendations on the limitation of exposure of the general public to EMF (0 Hz to 300 GHz)
2002	IEEE Recommended Practice for Measurements and Computations of Radio Frequency Electromagnetic Fields With Respect to Human Exposure to Such Fields, 100 kHz–300 GHz	IEEE	Revises and develops specifications for preferred methods for measuring and computing external radio frequency electromagnetic fields to which persons may be exposed
2002	ICNIRP Statement - General Approach to Protection against Non-Ionizing Radiation	ICNIRP	Optical radiation including lasers and electromagnetic fields, ultrasound and infrasound exposures
2004	Directive 2004/40/EC on Minimum Health and Safety Requirements Regarding the Exposure of Workers to the Risks Arising from Physical Agents (Electromagnetic Fields)	EC	Lays down minimum requirements for the protection of workers from risks to their health and safety arising or likely to arise from exposure to electromagnetic fields (0 Hz to 300 GHz) during their work
2004	ECC Recommendation (02)04 (revised 2007) Measuring Non-Ionising Electromagnetic Radiation (9 kHz – 300 GHz)	ECC	Describes a measurement method that should be used to assess electromagnetic radiation against the appropriate reference levels for exposure of human beings to electromagnetic fields (9 kHz – 300 GHz)
2005	IEEE Std C95.1-2005, Standard for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz to 300 GHz	IEEE	Exposure limits to protect against established adverse effects to human health induced by exposure to RF electric, magnetic and electromagnetic fields over the frequency range of 3 kHz - 300 GHz.
2006	The Electromagnetic Fields Human Exposure Act	WHO	Establishes limits on human exposure to Electromagnetic Fields (EMF) that will provide protection against known adverse health effects from any installation or device emitting such fields.
2006	Human EMF Exposure Limit Regulation	WHO	Protects the public and workers from adverse health effects arising from exposure to electromagnetic fields (EMF) in the living and working environments.
2006	The Electromagnetic Fields Human Exposure Act - Model legislation for electromagnetic fields protection	WHO	Establishes minimum requirements for the protection of the public and workers from risks to their health arising or likely to arise from their exposure to EMF in the frequency range 0 to 300 GHz.
2010	ICNIRP Guidelines for limiting exposure to time-varying electric and magnetic fields (1 HZ – 100 kHZ)	ICNIRP	Establishes guidelines for limiting exposure to electric and magnetic fields (EMF) that will provide protection against all established adverse health effects.
2013	Directive 2013/35/EU on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (electromagnetic fields)	EU	Minimum requirements for the protection of workers from risks to their health and safety arising, or likely to arise, from exposure to electromagnetic fields during their work
2014	IEEE Std C95.7-2014 Recommended Practice for Radio Frequency Safety Programs, 3 kHz to 300 GHz	IEEE	Guidance for preventing exposures above applicable radio frequency (RF) limits associated with RF sources that operate in the frequency range of 3 kHz to 300 GHz
2019	IEEE Std C95.1™-2019 Standard for Safety Levels with Respect to Human Exposure to Electric, Magnetic, and Electromagnetic Fields, 0 Hz to 300 GHz	IEEE	Exposure criteria and limits to protect against established adverse health effects in humans associated with exposure to electric, magnetic, and electromagnetic fields in the frequency range 0 - 300 GHz

Basic restrictions were based on health effects and the physical quantities used in this regard are specific absorption rate *SAR*, current density *J*, and power density *S* [5] (see Table 3):

- 1 Hz – 10 MHz – restrictions on current density to prevent effects on nervous system,
- 100 k Hz – 10 GHz – *SAR* against whole-body heat stress and excessive localized tissue heating,
- 10 – 300 GHz – power density – excessive heating in tissue at or near the body surface.

Table 3. Basic restrictions - ICNIRP Guidelines

Frequency range	Exposure category	Whole-body average SAR (W/kg)	Localised SAR in the head & trunk (W/kg)	Localised SAR in limbs (W/kg)	Current density for head and trunk (mA/m² rms)	Power density S (W/m²)
Up to 1 Hz	Occupational	-	-	-	40	-
	General public				8	
1 - 4 Hz	Occupational	-	-	-	40/f	-
	General public				8/f	
4 - 1000 Hz	Occupational	-	-	-	10	-
	General public				2	
1000 Hz - 100 kHz	Occupational	-	-	-	f/100	-
	General public				f/500	
100 kHz - 10 MHz	Occupational	0,4	10	20	f/100	-
	General public	0,08	2	4	f/500	
10 MHz - 10 GHz	Occupational	0,4	10	20	-	-
	General public	0,08	2	4	-	
10 GHz - 300 GHz	Occupational	-	-	-	-	50
	General public	-	-	-	-	10

Retrieved and processed after ICNIRP Guidelines, 1998

Reference levels are determined by extrapolation from the results of laboratory investigations or mathematical modelling from the basic restrictions, taking into account frequency, human body conductivity, size, shape, and position of the exposed body in the field (Table 4).

Council Recommendation 1999/519/EC introduced for EU general public basic restrictions and reference levels on exposure to radiations emitted by electromagnetic fields, excepting optical radiation and ionising radiation. This document covers the area of static fields, extremely low frequency fields ELF and radiofrequency fields RF, including microwaves, in the frequency range of 0 Hz to 300 GHz [6].

Basic restrictions on the exposure to time-varying fields, based on biological considerations and health effect, are represented by the specific absorption rate *SAR*, magnetic flux density *B*, current density *J* and power density *S* (See Table 5).

Reference levels derived from basic restrictions are electric field strength *E*, magnetic field strength *H*, power density *S* and limb current I_L. At certain frequencies, magnetic flux density *B* and power density *S*, are used as basic restrictions and reference levels. For pulsed fields it is used specific energy absorption *SA* (Table 6).

Table 4. Reference levels to time-varying electric and magnetic fields - ICNIRP Guidelines

Frequency range	Exposure category	E-field strength (V/m)	H-field strength (A/m)	B-field (μT)	Equivalent plane wave power flux density Seq (W/m2)	Maximum contact current (mA)	Induced current in any limbs (mA)
up to 1 Hz	Occupational	-	1.63×10^5	2×10^5			
	General public	-	3.2×10^4	4×10^4			
1 - 8 Hz	Occupational	20000	$1.63 \times 10^5/f^2$	$2 \times 10^5/f^2$			
	General public	10000	$3.2 \times 10^4/f^2$	$4 \times 10^4/f^2$			
8 - 25 Hz	Occupational	20000	$2 \times 10^4/f$	$2.5 \times 10^4/f$			
	General public	10000	$4000/f$	$5000/f$			
0.025 - 0.82 kHz	Occupational	$500/f$	$20/f$	$25/f$			
0.025 - 0.8 kHz	General public	$250/f$	$4/f$	$5/f$			
0.8 - 3 kHz	General public	$250/f$	5	6.25			
0.82 kHz - 65 kHz	Occupational	610	24.4	30.7			
3-150 kHz	General public	87	5	6.25			
0.065 - 1 MHz	Occupational	610	$1.6/f$	$2.0/f$			
0.15 - 1 MHz	General public	87	$0.73/f$	$0.92/f$			
1 MHz - 10 MHz	Occupational	$610/f$	$1.6/f$	$2.0/f$			
	General public	$87/f^{1/2}$	$0.73/f$	$0.92/f$			
10 MHz - 400 MHz	Occupational	61	0.16	0.2	10		
	General public	28	0.073	0.092	2		
400 MHz - 2 GHz	Occupational	$3f^{1/2}$	$0.008 f^{1/2}$	$0.01 f^{1/2}$	$f/40$		
	General public	$1.375 f^{1/2}$	$0.0037 f^{1/2}$	$0.0046 f^{1/2}$	$f/200$		
2 GHz - 300 GHz	Occupational	137	0.36	0.45	50		
	General public	61	0.16	0.20	10		
0 - 2.5 kHz	Occupational					1	
	General public					0.5	
2.5 kHz - 100 kHz	Occupational					$0.4 f$	
	General public					$0.2 f$	
100 kHz - 110 MHz	Occupational					40	
	General public					20	
10 - 110 MHz	Occupational						100
	General public						45

Table 5. Basic restrictions - Council Recommendation 1999/519/EC

Frequency range	Whole-body average SAR (W/kg)	Localised SAR in the head & trunk (W/kg)	Localised SAR in limbs (W/kg)	Magnetic flux density (mT)	Current density (mA/m² rms)	Power density S (W/m²)
0 Hz	-	-		40		-
>0 - 1 Hz	-	-	-	-	8	-
1 - 4 Hz	-	-	-	-	$8/f$	-
4 - 1000 Hz	-	-	-	-	2	-
1000 Hz - 100 kHz	-	-	-	-	$f/500$	-
100 kHz - 10 MHz	0.08	2	4	-	$f/500$	-
10 MHz - 10 GHz	0.08	2	4	-	-	-
10 GHz - 300 GHz	-	-	-	-	-	10

Source: Council Recommendation 1999/519/EC

Table 6. Reference levels - Council Recommendation 1999/519/EC

Frequency range	E-field strength (V/m rms)	H-field strength (A/m rms)	Equivalent plane wave power flux density Seq (W/m2)	Magnetic flux density B (μT)	Maximum contact current (mA rms)
0 - 1 Hz		$3{,}2 \times 10^4$		4×10^4	
0 - 2.5 kHz					0.5
1 - 8 Hz	10000	$3{,}2 \times 10^4/f^2$		$4 \times 10^4/f^2$	
2.5 kHz - 100 kHz					$0{,}2\,f$
8 - 25 Hz	10000	$4000/f$		$5000/f$	
0,025 - 0,8 kHz	$250/f$	$4/f$		$5/f$	
0,8 - 3 kHz	$250/f$	5		6.25	
3-150 kHz	87	5		6.25	
100 kHz - 110 MHz					20
0,15 - 1 MHz	87	$0.73/f$		$0.92/f$	
1 MHz - 10 MHz	$87/f^{1/2}$	$0.73/f$		$0.92/f$	
10 MHz - 400 MHz	28	0.073	2	0.092	
400 MHz - 2 GHz	$1.375\,f^{1/2}$	$0.0037\,f^{1/2}$	$f/200$	$0.0046\,f^{1/2}$	
2 GHz - 300 GHz	61	0.16	10	0.20	

Retrieved and processed after Council Recommendation 1999/519/EC

In a study released in 2017, Stam identified three groups of countries in European Union, regarding the EMF policies in member states and their relationship with this recommendation, in what it concerns exposure of the general public [7]:

- Group 1 - recommendation has been transposed in binding national legislation or national policy,
- Group 2 - national limits based on recommendation or ICNIRP are not binding, there is no regulation or there are more lenient limits, and
- Group 3 - stricter basic restrictions or reference levels based on precautionary principle or due to public pressure (see Table 7).

Table 7. EMF Policies in EU Member States – exposure of general public

Type of exposure	Category of EU Members States		
	Group 1 - legal limits based on 1999/519/EC	Group 2 - no legal limits or limits less strict than in 1999/519/EC	Group 3 - stricter limits than in 1999/519/EC
Power frequency fields	Czech Republic, Estonia, France, Germany, Greece, Hungary, Ireland, Luxemburg, Portugal, Romania, Slovakia	Austria, Cyprus, Denmark, Finland, Latvia, Malta, Netherlands, Spain, Sweden, United Kingdom	Belgium, Bulgaria, Croatia, Italy, Lithuania, Poland, Slovenia
Radiofrequency fields	Cyprus, Czech Republic, Estonia, Finland, France, Germany, Hungary, Ireland, Malta, Portugal, Romania, Slovakia, Spain	Austria, Denmark, Latvia, Netherlands, Sweden, United Kingdom	Belgium, Bulgaria, Croatia, Greece, Italy, Lithuania, Luxemburg, Poland, Slovenia

Source: Edited based on *Stam, R., Comparison of international policies on electromagnetic fields (power frequency and radiofrequency fields), 2017*

On the other hands, related to occupational exposure, the EU Member States use national legislation based on directive 2013/35/EU, that established minimum requirements, but allowing, in the same time, the possibility to set stricter limits or rules. In this direction, there are two exceptions, Poland and Czech Republic that use different action levels or exposure limit values.

In Spain, in 2001, it is issued a regulation, Real Decreto 1066/2001 [8], that established conditions for the protection of the public against radioelectric emissions, updated in 2017.

There had been used as basic restrictions the restrictions on exposure to time-varying electric, magnetic, and electromagnetic fields, based directly on known health effects and biological considerations.

In order to specify these constraints, there were used as physical quantities magnetic induction *B*, current density *J*, specific energy absorption index *SAR* and power density *S* (see Table 8).

Table 8. Basic restrictions for general public – Spain

Frequency range	Whole-body average SAR (W/kg)	Spatial peak SAR in the head & trunk (W/kg)	Spatial peak SAR in limbs (W/kg)	Current density in the head and trunk (mA/m² rms)	Magnetic induction (mT)	Instantaneous power flux density (W/m²)
0 Hz					40	
>0 - 1 Hz				8		
1 - 4 Hz				8/*f*		
4 - 1000 Hz				2		
1000 Hz - 100 kHz				*f*/500		
100 kHz - 10 MHz	0.08	2	4	*f*/500		
10 MHz - 10 GHz	0.08	2	4			
10 GHz - 300 GHz						10

Source: Real Decreto 1066/2001

The reference levels, used to determine the probability that the basic restrictions will be exceeded are (see Table 9):

1. derived quantities from relevant basic restrictions, using measurements or computerized techniques: electric field intensity *E*, magnetic field intensity *H*, magnetic induction *B*, power density *S* and limb current I_l;
2. quantities that refer to perception and other adverse indirect effects to exposure to radioelectric emissions, respectively contact current *Ic* and, for pulsatile fields, specific energy absorption *SA* [8].

Table 9. Reference levels for general public – Spain

Frequency range	E-field strength (V/m rms)	H-field strength (A/m rms)	Equivalent plane wave power flux density Seq (W/m2)	Magnetic induction B (μT)	Maximum contact current (mA rms)
0 - 1 Hz		3.2×10^4		4×10^4	
1 - 8 Hz	10000	$3.2 \times 10^4/f^2$		$4 \times 10^4/f^2$	
8 - 25 Hz	10000	$4000/f$		$5000/f$	
0.025 - 0.8 kHz	$250/f$	$4/f$		$5/f$	
0,8 - 3 kHz	$250/f$	5		6.25	
3-150 kHz	87	5		6.25	
0,15 - 1 MHz	87	$0.73/f$		$0.92/f$	
1 MHz - 10 MHz	$87/f^{1/2}$	$0.73/f$		$0.92/f$	
10 MHz - 400 MHz	28	0.073	2	0.092	
400 MHz - 2 GHz	$1.375 f^{1/2}$	$0.0037 f^{1/2}$	$f/200$	$0.0046 f^{1/2}$	
2 GHz - 300 GHz	61	0.16	10	0.20	
0 - 2.5 kHz					0.5
2.5 kHz - 100 kHz					$0.2 f$
100 kHz - 110 MHz					20

Retrieved and processed after Real Decreto 1066/2001

As it can be seen, the basic restrictions and reference values are similar to those from Council Recommendation 1999/519/EC.

The same situation can be revealed in Romania, where in 2006 Minister of Public Health issued Order no. 1193/2006 for the approval of the Norms regarding the limitation of the exposure of the general population to electromagnetic fields from 0 to 300 GHz [9].

In addition, Romanian Government in 2016 issued a decision HG 520/2016 [10] on minimum safety and health requirements regarding the exposure of workers to risks generated by electromagnetic fields in accordance with Directive 2013/35/EU. In 2018, Institute of Public Health subordinated to Ministry of Health published a practical guide for conformity assessment with national exposure rules of workers in electromagnetic fields [11].

In Australia, in 2002 ARPANSA Australian Radiation Protection and Nuclear Safety Agency issued Radiation Protection Standard for Maximum Exposure Levels to Radiofrequency Fields — 3 kHz to 300 GHz which sets limits for human exposure to radiofrequency (RF) fields in the frequency range 3 kHz to 300 GHz, to prevent adverse health effects [12].

Table 10. Basic restrictions in Australia – occupational and general public

Frequency range	Exposure category	Whole-body average SAR (W/kg)	Spatial peak SAR in the head & torso (W/kg)	Spatial peak SAR in limbs (W/kg)	Spatial peak SA in the head within any 50 μs interval (mJ/kg)	Instantaneous spatial peak SAR in the head and torso (W/kg)	Current density in the head and torso (mA/m² rms)	Time averaged power flux density (W/m²)	Instantaneous power flux density (W/m²)
3 kHz - 10 MHz	Occupational						10 x f		
	General public						2 x f		
100 kHz - 6 GHz	Occupational	0.4	10	20					
	General public	0.08	2	4					
300 MHz - 6 GHz	Occupational				10				
	General public				2				
10 MHz - 6 GHz	Occupational					10000			
	General public					2000			
6 GHz - 300 GHz	Occupational							50	50000
	General public							10	10000

Retrieved and processed after ARPANSA Standard, 2002

In order to develop basic restrictions (see Table 10), there had been taken into consideration different criteria:

- 3 kHz – 10 MHz – restrictions on instantaneous rms current density to prevent electrostimulation of excitable tissues,
- 100 kHz – 6 GHz – whole body average *SAR* against whole-body heat stress, spatial peak SAR in head, trunk and limbs against excessive localised temperature rise in tissue,
- 300 MHz – 6 GHz, for pulse modulated exposure – specific absorption *SA* per pulse for localised exposures to the head to avoid or limit auditory effects,
- 10 MHz – 6 GHz – instantaneous spatial peak *SAR* against associated effects to extremely high-level pulse fields,
- 6 GHz – 300 GHz – instantaneous and time averaged incident power flux density to prevent excessive heating in tissue at or near the body surface and to protect against associated effects to extremely high-level pulse fields [12].

In the Australian standard *E* and *H* reference levels are established for time averaged and instantaneous exposure to rms electric and magnetic fields and are derived from basic restrictions by mathematical modelling and laboratory investigations. In addition, there are set reference levels for instantaneous rms contact current and time averaged rms current induced in any limb over 6-minute period (see Table 11).

Table 11. Reference levels in Australia – occupational and general public

Frequency range	Exposure category	Time averaged exposure to rms electric and magnetic fields (unperturbed fields)			Exposure to instantaneous rms electric and magnetic fields (unperturbed fields)			Time averaged rms	Instantaneous rms contact
		E-field strength (V/m rms)	H-field strength (A/m rms)	Equivalent plane wave power flux density Seq (W/m2)	E-field strength (V/m rms)	H-field strength (A/m rms)	Equivalent plane wave power flux density Seq (W/m2)	Current (mA rms)	Maximum contact current (mA rms)
3 Khz – 65 kHz	Occupational				614	25.0	-		
3 kHz – 100 kHz	Occupational							$0.4\times f$	
	General public				86.8	4.86	-	$0.2\times f$	
65 kHz – 100 kHz	Occupational				614	$1.63 / f$	-		
100 kHz - 150 kHz	General public	86.8	4.86	-	$488\times f^{0.75}$	4.86	-		
100 kHz - 1 MHz	Occupational	614	$1.63 / f$	-	$3452\times f^{0.75}$	$9.16 / f^{0.25}$	-		
100 kHz - 110 MHz	Occupational							40	
	General public							20	
150 kHz - 1 MHz	General public	86.8	$0.729 / f$	-	$488\times f^{0.75}$	$3.47 / f^{0.75}$	-		
1 MHz - 10 MHz	Occupational	$614 / f$	$1.63 / f$	$1000 / f^2$	$3452\times f^{0.25}$	$9.16 / f^{0.25}$	$(10^9 / f)^{0.5}$		
	General public	$86.8 / f^{0.5}$	$0.729 / f$	-	$488\times f^{0.25}$	$3.47 / f^{0.75}$	-		
10 MHz - 110 MHz	Occupational								100
	General public								45
10 MHz - 400 MHz	Occupational	61.4	0.163	10	1941	5.15	10000		
	General public	27.4	0.0729	2	868	2.30	2000		
400 MHz - 2 GHz	Occupational	$3.07\times f^{0.5}$	$0.00814\times f^{0.5}$	$f / 40$	$97\times f^{0.5}$	$0.258\times f^{0.5}$	$25\times f$		
	General public	$1.37\times f^{0.5}$	$0.00364\times f^{0.5}$	$f / 200$	$43.4\times f^{0.5}$	$0.115\times f^{0.5}$	$5\times f$		
2 GHz - 300 GHz	Occupational	137	0.364	50	4340	11.5	50000		
	General public	61.4	0.163	10	1941	5.15	10000		

Retrieved and processed after ARPANSA Standard, 2002

In European Union, Directive 2004/40/EC emphasizes the need to assess the risk of workers' exposure by the employer. The directive introduced the term "exposure limit values" defined as "limits on exposure to electromagnetic fields which are based directly on established health effects and biological considerations", a term similar to "basic restrictions" used in other documents in the field [13].

The exposure limit values in this directive established for worker's exposure to electromagnetic fields are also similar to those set as basic restrictions for occupational exposure in other documents: whole body average *SAR*, head and trunk localized *SAR*, limbs localized *SAR*, current density, and power density (see Table 12).

Depending on frequency, they are set in order to prevent the following effects:

- cardiovascular and central nervous system, for time-varying fields up to 1 Hz,
- on central nervous system functions, for 1 – 10 MHz,
- excessive localised heating of tissues and whole-body heat stress, for 100 kHz – 10 GHz,
- excessive localised heating at or near the body surface, for 10 GHz – 300 GHz [13].

Table 12. Exposure limit values according to Directive 2004/40/EC

Frequency range	Whole-body average SAR (W/kg)	Localised SAR in the head & trunk (W/kg)	Localised SAR in limbs (W/kg)	Current density for head and trunk J (mA/m²) (rms)	Power density S (W/m²)
Up to 1 Hz	-	-	-	40	-
1 - 4 Hz	-	-	-	40/f	-
4 - 1000 Hz	-	-	-	10	-
1000 Hz - 100 kHz	-	-	-	f/100	-
100 kHz - 10 MHz	0,4	10	20	f/100	-
10 MHz - 10 GHz	0,4	10	20	-	-
10 GHz - 300 GHz	-	-	-	-	50

Source: Directive 2004/40/EC

For directly measured elements *E, H, B* and *S*, in directive is used the term "action values". These values are similar to reference values of ICNIRP Guidelines/1998, based on the rationale used by that (See Table 13).

Table 13. Action values according to Directive 2004/40/EC

Frequency range	Electric field strength E (V/m)	Magnetic field strength H (A/m)	Magnetic flux density B (μT)	Equivalent plane wave power flux density Seq (W/m2)	Contact current I_c(mA)	Limb induced current I_L (mA)
0 - 1 Hz	-	1.63×10^5	2×10^5	-	1.0	
1 - 8 Hz	20000	$1.63 \times 10^5/f^2$	$2 \times 10^5/f^2$	-	1.0	
8 - 25 Hz	20000	$2 \times 10^4/f$	$2.5 \times 10^4/f$	-	1.0	
0.025 - 0.82 kHz	500/*f*	20/*f*	25/*f*	-	1.0	
0.82 kHz - 2.5 kHz	610	24.4	30.7	-	1.0	
2,5 kHz - 65 kHz	610	24.4	30.7	-	0.4 *f*	
65 kHz - 100 kHz	610	1600/*f*	2000/*f*	-	0.4 *f*	
0.1 - 1 MHz	610	1.6/*f*	2.0/*f*	-	40	
1 MHz - 10 MHz	610/*f*	1.6/*f*	2.0/*f*	-	40	
10 MHz - 110 MHz	61	0.16	0.2	10	40	100
110 MHz - 400 MHz	61	0.16	0.2	10	-	
400 MHz - 2000 Hz	$3f^{1/2}$	$0.008 f^{1/2}$	$0.01 f^{1/2}$	*f*/40	-	
2 GHz - 300 GHz	137	0.36	0.45	50	-	

Source: Directive 2004/40/EC

The Directive 2004/40/EC was replaced in 2013 by the Directive 2013/35/EU [1]. This directive established exposure limit values ELV (see Table 14), based on biophysical and biological considerations, in relation with thermal and non-thermal effects. However, as the other regulations and documents, it does not address long-term effects of EMF exposure.

These ELVs comprise health effects ELVs, above which employees might be affected by thermal heating or stimulation of nerve or muscle tissue, and sensory effects ELVs, when they might be subject to transient disturbed sensory perceptions and minor changes in brain functions [1].

Table 14. Exposure limit values according to Directive 2013/35/EU

Category of effects	Frequency range	Subcategories of effects	B (T)	E (V/m)	SAR (W/kg)	SA (mJ/kg)	S (W/m^2)	Observations
Non-thermal effects	0 - 1 Hz)	Sensory effects - vertigo and other physiological effects	2	-	-	-	-	Normal working conditions
			8	-	-	-	-	Localised limbs exposure
		Health effects	8	-	-	-	-	Controlled working conditions - is applicable on a temporary basis during the shift when justified by the practice or process,
	[1 Hz - 3 kHz)	Health effects - electric stimulation of all peripheral and central nervous system tissues in the body, including the head	-	1.1	-	-	-	spatial peak values in the entire body of the exposed subject
	[3 kHz - 10 MHz]		-	$3.8 \times 10^{-4} f$	-	-	-	
	[1 Hz - 10 Hz)	Sensory effects - on the central nervous system in the head	-	$0.7/f$	-	-	-	spatial peak values in the head of the exposed subject
	[10 Hz - 25 Hz)		-	0.07	-	-	-	
	[25 Hz - 400 Hz)		-	$0.0028f$	-	-	-	
Thermal effects	100 kHz - 6 GHz	Health effects - whole body heat stress	-	-	0.4	-	-	expressed as averaged SAR in the body
		Health effects - localised heat stress in head and trunk	-	-	10	-	-	expressed as localised SAR in the body
		Health effects - localised heat stress in the limbs	-	-	20	-	-	expressed as localised SAR in the limbs
	[0.3 - 6 GHz]	Sensory effects - auditory effects caused by exposures of the head to pulsed microwave radiation	-	-	-	10	-	localised specific energy absorption - averaging mass is 10 g of tissue
	[6 - 300 GHz]	Health effects	-	-	-	-	50	6 - 10 GHz are to be averaged over any six-minute period; >10 GHz shall be averaged over any $68/f^{1.05}$-minute period

Retrieved and processed after Directive 2013/35/EU

Regarding the term action levels ALs, also used in the previous directive, the ALs are presented separately for non-thermal and thermal effects.

For non-thermal effects, there are used ALs values for electric field strength, magnetic flux density for static and time-varying density, and contact current (see Table 15).

This document introduces, also, for electric fields low and high ALs related to specific protection or prevention measures, and for magnetic fields, low ALs in relation to sensory effects ELVs and high ALs to health effects ELVs. ALs for electric field represent maximum calculated or measures values at the workers' body position and these are established [1].

Table 15. Action values related to non-thermal effects according to Directive 2013/35/EU

Type of ALs	Frequency range	Low ALs E (V/m) RMS	High ALs E (V/m) RMS	Low ALs B (μT) RMS	High ALs B (μT) RMS	ALs for exposure of limbs (μT) RMS	ALs (I_C) (mA) RMS	ALs (B_0) (mT)	Observations
Exposure to electric fields	[1 - 25 Hz)	2.0×10^4	2.0×10^4	-	-	-	-	-	
	[25 - 50 Hz)	$5.0 \times 10^5/f$	2.0×10^4	-	-	-	-	-	
	[50 Hz - 1.64 kHz)	$5.0 \times 10^5/f$	$1.0 \times 10^6/f$	-	-	-	-	-	
	[1.64 - 3 kHz)	$5.0 \times 10^5/f$	6.1×10^2	-	-	-	-	-	
	[3 kHz - 10 MHz]	1.7×10^2	6.1×10^2	-	-	-	-	-	
Exposure to magnetic fields	[1 - 8 Hz)	-	-	$2.0 \times 10^5/f^2$	$3.0 \times 10^5/f$	$9.0 \times 10^5/f$	-	-	Exposure of limbs to a localised magnetic field
	[8 - 25 Hz)	-	-	$2.5 \times 10^4/f$	$3.0 \times 10^5/f$	$9.0 \times 10^5/f$	-	-	
	[25 - 300 Hz)	-	-	1.0×10^3	$3.0 \times 10^5/f$	$9.0 \times 10^5/f$	-	-	
	[300 Hz - 3 kHz)	-	-	$3.0 \times 10^5/f$	$3.0 \times 10^5/f$	$9.0 \times 10^5/f$	-	-	
	[3 kHz - 10 MHz]	-	-	1.0×10^2	1.0×10^2	3.0×10^2	-	-	
Contact current	up to 2.5 kHz	-	-	-	-	-	1.0	-	Steady state contact current
	[2.5 - 100 kHz)	-	-	-	-	-	$0.4f$	-	
	[100 - 10000 kHz)	-	-	-	-	-	40	-	
Exposure to static magnetic fields	0 Hz	-	-	-	-	-	-	0.5	Interference with active implanted devices
		-	-	-	-	-	-	3	Attraction and projectile risk in the fringe field of high field strength sources (> 100 mT)

Retrieved and processed after Directive 2013/35/EU

For thermal effects, there had been specified as action values electric field strength and magnetic flux density of time varying electric, respectively magnetic fields, power density of electromagnetic waves and contact current (see Table 16). Of these, only the limb induced current has exactly the same value as in the previous directive.

Table 16. Action values related to thermal effects according to Directive 2013/35/EU

Type of ALs	Frequency range	ALs E (V/m) RMS	ALs B (μT) RMS	ALs S (W/m^2)	ALs (I_C) (mA) RMS	ALs I_L (mA)	Observations
Exposure to electric and magnetic fields	[100 kHz - 1 MHz)	6.1×10^2	$2.0 \times 10^6/f$	-	-	-	
	[1 - 10 MHz)	$6.1 \times 10^8/f$	$2.0 \times 10^6/f$	-	-	-	
	[10 - 400 MHz)	61	0.2	-	-	-	
	[400 MHz - 2 GHz)	$3 \times 10^{-3}/f^{1/2}$	$1 \times 10^{-5}/f^{1/2}$	-	-	-	
	[2 - 6 GHz)	1.4×10^2	4.5×10^{-1}	-	-	-	
	[6 - 300 GHz]	1.4×10^2	4.5×10^{-1}	50	-	-	
Contact and induced limb currents	[100 kHz - 10 MHz)	-	-	-	40	-	Steady state contact current
	[10 - 110 MHz]	-	-	-	40	100	Induced limb current in any limb

Retrieved and processed after Directive 2013/35/EU

The latest standard issued by the IEEE in 2019 IEEE Std C95.1™-2019, which establishes safety levels regarding human exposure to electromagnetic fields, brings some changes, including terminology, compared to the previous standard in 2005.

The term "basic restrictions" is replaced by "dosimetric reference limit" DRL and "maximum permissible exposure" MPE by "exposure reference level" ERL. The IEEE Standard addresses three frequency bands: 0 – 100 kHz, 100 kHz – 6 GHz, and 6 GHz – 300 GHz in approaching biological effects of exposure [14]. It is not just a standard that applies to persons permitted in restricted environments and to the general public in unrestricted environments, but also an extensive, documented scientific work, extremely useful for researchers in the field.

3. CONCLUSIONS

Although the harmonization process began more than 20 years ago, there are still notable differences between the different states of the world, the differences being sometimes significant even at the level of a continent or a region.

However, in the European Union, Recommendation 1999/519/EC and Directive 2013/35/EU open the way for a harmonization of Member States' regulations, even if there are still some different approaches of EMF policies. Moreover, these regulations, recommendations and guidelines do not limit Member States in introducing more restrictive measures.

It can be observed, also, attempts of harmonization in the elaboration of different standards and regulations at the level of national and international bodies in the field, by taking into account the points of view, the reference elements and the studies on which other worldwide regulations are based.

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