Background

This Chapter 9 is the April 2021 revised edition, retrieved from Mazar 'Wiley' book 'Radio Spectrum Management: Policies, Regulations and Techniques'; see Amazon. The Author serves as ITU intersector coordinator on RF-EMF and co-rapporteur for ITU-D Question 7/2.

Those are the ICNIRP Guidelines:

1. ICNIRP (1998): Guidelines for limiting exposure to time-varying electric, magnetic and electromagnetic fields (up to 300 GHz);
2. ICNIRP (2010): Guidelines for limiting exposure to time-varying electric and magnetic fields (1 Hz – 100 kHz);
3. ICNIRP (2020): Guidelines for limiting exposure to electromagnetic fields (100 kHz to 300 GHz).

The limits below 100 kHz are the ones published in ICNIRP (2010). With the publication of the 2020 RF guidelines, the 1998 guidelines have become obsolete.

After the Revisions of IEEE C95.1-2019 and ICNIRP 2020, this Chapter revises mainly Section 9.3 'International Exposure Limits; ICNIRP Guidelines and IEEE Standard'. Additional changes are inserted as the first 5G New Radio version was officially released in Dec. 2017, and millimeter-wave 5G technologies. All hyperlinks are reviewed. This revision uses material from the Draft Report of Question 7/2 to WTDC and ITU October 2020 'Background Paper, ITU regional forum for Europe: 5G strategies, policies, and implementation'.

Some Publications of the Author on EMF

ITU Conferences and Workshops on EMF

1. A Comparison Between European and North American Wireless Regulations, presentation at the 'Technical Symposium at ITU Telecom World 2011' www.itu.int/worl2011; the slides presentation, 27 October 2011
2. 2016 ITU R-D-T 'Intersectoral activities on human exposure to EMF'; Bangkok, 26 April 2016
3. 2017 ITU Workshop '5G, EMF & Health'; Warsaw, Poland, 5 December 2017
4. 2018 ITU workshop 'modern policies, guidelines, regulations and assessments of human exposure to RF-EMF'; Geneva, Switzerland, 10 October 2018 ; see slide
5. PRIDA Track 1 (T1) On-line English workshop 20thApril–1st May2020. First_week_slides_v2; see pp. 237–296, EMF presentation 24 April 2020
6. PRIDA Track 1 (T1) Atelier de renforcement des capacités sur la gestion moderne du spectre 11-22 mai 2020. First_week_slides_v2; see pp. 224–278, EMF présentation 15 mai 2020
7. ITU Regional Forum for Europe on 5G Strategies, policies and implementation; 22-23 Oct 2020; 'RF Human Hazards; EMFs Implementing 5G for Good: Does EMF Matter?'

Other Papers and Presentations on EMF

1. This 2021Chapter 9 on EMF exposure of my Wiley book on Spectrum Management
2. Human RF Exposure Limits: Reference Levels in Europe, USA, Canada, China, Japan and Korea EMC Europe 2016; Wroclaw, Poland, 9 Sept. 2016
3. Regulation of RF Human Hazards Lusaka, Zambia; 13 January 2017
4. EMF Concerns and Perceptions Modiin, Israel; 25 March 2019
5. EMF, New ICNIRP Guidelines and IEEE C95.1-2019 Standard: Differences and Similarities; Warsaw, Poland; 3 Dec 2019
6. Module on EMF to the ITU Spectrum Training; April 2020
7. EMF_HumanHazardsPresentation_MaccabimMazar9June2020.pdf
8. Academic_Course_Advanced_Wireless_Communications_Mazar3_Regulation_EMC_HumanHazards_2020.pdf
9. 2020 IEEE Israel Conference on Electromagnetic Compatibility (EMC), 15 Oct. 2020; Updated Human Exposure Standards IEEE 2019 and ICNIRP 2020, towards 5G applications
10. ITU mission 26146 October 2020 'Implementing 5G for Good: Does EMF Matter?'

Dr. Haim Mazar (Madjar); 22 April 2021

Chapter number **9**

9. Chapter Title: Limitations to Radio Frequency Human Exposure

Contents

9.1 Introduction

The proliferation of cellular base stations and wireless fixed installations around the world (see Figure 9.1 Global mobile-cellular telephone subscription rate), the public dislike of large antenna structures and the growing concern against electromagnetic pollution has led to constraining legislations and regulations to ensure protection of the public. Human-hazards have become a significant health and safety issue to regulators, service providers and wireless equipment suppliers. Populations are exposed to electromagnetic fields (EMF), the levels of which continue to increase due to more wireless systems (such as Wi-Fi). Limitations to Radio Frequency (RF) human exposure contain restrictions on exposure that are intended to assist those with responsibility for the safety of the general public and workers. The dominant sources of human exposure to RF radiation are near-field wireless sources for workers; and transmitters operating on or in close vicinity to the body, such as hand-held devices, for the general population. Wireless communications use electromagnetic waves in RF ranges of the spectrum, which are of much lower frequencies compared to ionizing radiation[1], such as X-rays or Gamma-rays. As such, RF waves do not have enough energy to either break molecular bonds or even cause ionization of atoms in the human body; hence, their classification as non-ionizing radiation (NIR).

The short-term thermal heating capabilities of RF (e.g., microwave ovens) are well known. The question is whether there are some other long-term health effects, e.g., cancer. While some studies have indicated the possibilities of non-thermal effect in living organism, they have never been substantiated. It is known that radio waves, at current frequency ranges used on mobile phones, cause vibration of polarised molecules, e.g., water, and thus through induced friction forces they cause heat to be developed at tissues surrounding the device's antenna. The international agency for research on cancer (IARC)[2] took a conservative approach by labelling Radio Frequencies (RF) as Category 2B (like coffee); *i.e.*, 'possibly carcinogenic to humans' (World Health Organization WHO 2011).

The main tool for RF gauging the impact of NIR on human tissues is the 'Specific Absorption Rate' (SAR), *i.e.*, average RF power absorbed in a unit mass of the human tissue; 'electric field-strength' and 'power-density' parameters are directly derived from SAR and serve to calculate and measure the human exposure from base stations.

Some countries (and cities) adopt higher profiles (lower RF thresholds) which lead to severe restrictions on EMF, that are at odds with those of the international community.

The international commission on non-ionizing radiation protection (ICNIRP)[3] Guidelines are backed by WHO, and constitute the current scientific consensus. Nevertheless, national regulations have a priority status in their countries; as influenced by social-economic-political factors, the values adopted in each country may vary. The vast majority of countries have adopted RF-EMF exposure limit values based on the ICNIRP guidelines or IEEE standards; however, some countries have decided to adopt additional measures in order to protect their population. There is no scientific reason to use different exposure limits in different countries. Administrations are encouraged to follow the guidelines set by the science-based ICNIRP and

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[1] Electromagnetic radiation at frequencies above the ultra-violet band are classified as 'ionizing radiation', because when incident on matter they have enough energy to effect changes in the atoms, by liberating ionizing electrons and thus altering their chemical bonds. Ionizing radiation occurs at frequencies above 2,900 THz ($2{,}900\times10^{12}$ Hz). This frequency limit corresponds to a wavelength of about 103.4 nm; and minimum ionization energy of 12eV. Plank constant relates the electromagnetic radiation to the frequency of that radiation. Proof of f_{min}: since Plank constant h equals 4.135 667 516 x 10^{-15} electron-Volt second, and the Plank-Einstein relation energy $e=hf$, the minimum frequency f of ionizing radiation 12/(4.135 667 516 x 10^{-15}) equals $2.9\text{x}10^{15}$ Hz, 2,900 TeraHz.

[2] IARC is an inter-governmental and inter-disciplinary agency, whose objective is to promote international collaboration in cancer research. IARC is part of the World Health Organization of the United Nations.

[3] ICNIRP is an international body of independent scientific experts specialized in non-ionizing radiation protection. ICNIRP addresses the important issues of possible adverse effects on human health of exposure to non-ionizing radiation

IEEE expert groups, or limits set by their own experts. The best practice for Administrations that choose to use international RF-EMF exposure limits is to limit the exposure levels to the thresholds specified in ICNIRP (2020) Guidelines.

This chapter is a specialist area; it is significant to the spectrum managers and policy makers, as stringent policies, regulations and approaches affect the provision of radio services. There are countless studies on EMF risks; this chapter focuses on policies and regulations without entering the biological arena.

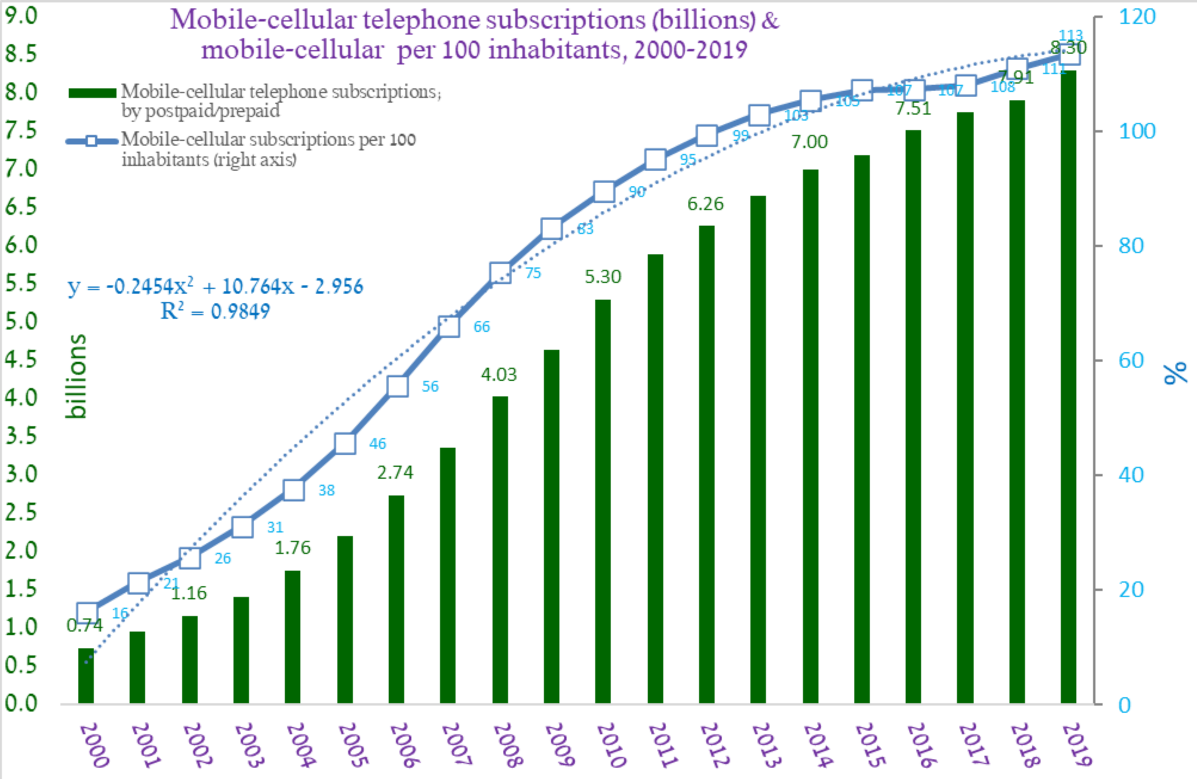
Despite ICNIRP guidelines and IEEE Standard to limit the exposure to EMF, parts of the public have remained concerned, on the basis that there exists no proof that these threshold levels are safe, as no all-possible health effects were studied. While, absolute proof does not logically exist, national regulators are placed under public pressure. To answer this dilemma, some countries apply the precautionary-principle to restrict the human-hazards thresholds. As an example, the UK Regulator formed the Stewart Committee, which consisted of a group of independent experts; the committee recommended applying the precautionary-approach to the EMF health risk management problem. This approach may replace the two-state risk management model (above/below the threshold), allowing the introduction of other factors; it is a trade-off balance between the remaining uncertainty (and the damage in the case that the worst-case turns true), versus implementing stricter requirements (resources and reduced quality of service).

Evidence of the proliferation of cellular base stations around the world can be gleaned from the following figure (based on ITU indicators[4]), which depicts mobile-cellular subscriptions and world-average cellular penetration per 100 inhabitants, years 2000 to 2019. The 24th Edition/December 2020 indicates that there were 8.3 billion subscribers in 2019 and 111 cellular telephone subscriptions per 100 inhabitants. As an indication, roughly every 1 000 subscribers need one cellular mast,[5] and it is estimated that there are more than 8 million base stations around the world; ; see footnote 69.

[4] ITU. World Telecommunication/ICT Indicators Database. https://www.itu.int/en/ITU-D/Statistics/Pages/publications/wtid.aspx

[5] See H. Mazar (2016), op. cit., Chapter 9, section 9.7.2

Figure 9.1 Global mobile-cellular telephone subscription rate



9.2 RF Health Risks as a Social Story

9.2.1 *Electromagnetic hypersensitivity and electrophobia*

The EMF controversy is a social issue more than a strictly scientific one, as safety is a concept that is more social than scientific. Evidence is propelled by feelings and beliefs derived from values, moral principles and knowledge, rather than facts established by result of studies of biological processes. Also, the reaction of people is selective and inconsistent; we live in a society shaped by consumer health and ecological anxieties. Psychology may explain why some people react negatively toward newly deployed technologies; see the reaction to the installations of 5G base stations. It is sometimes quite an irrational attitude (and phobia?) associated with a number of possible hazards; e.g., the invisible EMF can be compared to a childish fear of the dark and the unknown, a ‘phantom risk’.

Although no causal link with exposure to EMFs or waves has been established, individuals report a variety of health problems and mild symptoms, and react by avoiding the RF fields as best they can; others are so severely affected that they cease work and change their entire lifestyle. This reputed sensitivity to EMF has been generally termed ‘electromagnetic hypersensitivity’ (EHS). EHS is characterized by a variety of non-specific symptoms, which afflicted individuals attribute to exposure to EMF. The symptoms are certainly real and can vary widely in their severity; see WHO 2005. WHO recognises that EMF intolerance is a medical condition, and that electro sensitivity is a clinical situation, whereby sufferers are entitled to compensation. The council of Europe, Resolution 1815 (2011) §8.1.4 recommends that member states “pay particular attention to ‘electrosensitive’ people who suffer from a syndrome of intolerance to EMF and introduce special measures to protect them, including the creation of wave-free areas not covered by the wireless network”. EMF hypersensitivity can occur as a *bona fide* environmentally inducible neurological syndrome; see conclusion of Int J Neurosci. 2011. Countries may set areas electrosanitized, so persons with electro hypersensitivity may have the opportunity to live and work in an electrosanitized environment.

As will be described in a subsequent paragraph 9.8.3, the common public fear is also based on many myths, which are not in line with reality. In any case the Christmas 2020 Nashville bombing (due to conspiracy theory that 5G is killing people ?) has underscored how vulnerable communications infrastructure remains nearly two decades after the Sept. 11, 2001.

9.2.2 *Regulating uncertain risks*

The main concern for regulators is about regulating uncertain risks from EMF radiating from mobile phones, cellular or broadcasting towers and amateurs' transmitters. The significant precedent for reactions against cell-phone emissions was propelled by suspicions about electricity pylons[6]; similar ecological pressure groups are campaigning against both types of radiation. The opposition to the erection of both 'threats' are developed on a largely economic and classically environmental basis. Demands for relocation of these 'polluters' are based on health fears, as much as on concern about their impact on the devaluation of property prices, open fields, beauty of the landscape (impact on visual amenity) and even democracy's factor- their construction without consultation (Burgess 2006 p.339).

The management of RF human-hazards is a problem of reconciling the roles of science (by the 'weight of evidence', *i.e.*, the ICNIRP threshold levels) and risk assessment (the adopted values of each country). Science is the most powerful, objective and effective agent to provide a universal base for systematic knowledge. However, by definition, science cannot prove the 'null' or 'empty' group: in our case, the inexistence of harm. Hence, 'it is impossible to scientifically prove absolute safety (the null hypothesis)'[7]. For example, 'with regard to non-thermal interactions, it is in principle impossible to disprove their possible existence but the plausibility of the various non-thermal mechanisms that have been proposed is very low' (ICNIRP 2009 Statement p.257). The national thresholds and recommended limits are related to the national tolerability to risks, governmental and policy orientations. The adopted thresholds reveal the public trust (the Commentary of Slater in Lofstedt and Vogel 2001 p.410), the level of confidence in their states and institutions, and in their ability to resolve problems (Burgess 2003 p.15 and 2004 p.14). Trusting styles (of the public toward the regulator) may lead to less precaution (and thus higher threshold levels, or none at all), while more antagonistic styles (including mistrust of regulators and public toward science) lead to lower protection thresholds (meaning more restrictive emissions). Moreover, trusting is linked to the presumption of innocence; less precaution is typical to the 'innocent until proven guilty' way of thinking: there are no EMF hazards to the health of humans until the risks are scientifically determined and proven. In contrast, the more restrictive countries presume worst-case scenarios and that EMF are 'guilty until proven not-guilty': RF emissions cause severe human-hazards; therefore, the RF limits to exposure levels should be reduced. The conflicting policies are also derived from different rationalities and worldviews (Mazar 2009 p. 200).

SAR measurements for compliance purposes under laboratory conditions with devices configured to operate at maximum powers show values close to the limits. However, the compliance SAR values reported for each model of mobile phone overstate real-life exposure levels. In reality, the devices operate at significantly lower power levels especially in areas of good reception. Mobile phone users tend to be exposed to much higher levels of radiation from their handsets than from masts, because we are much closer to the RF source. The main societal difference between the radiation from the cellular terminal (SAR) and base station is that the cellular utilisation is voluntary (it is our choice to use cellular phone) and the base station's

[6] Utility transmission lines (power lines) and high power apparatuses (generators, transformers) produce magnetic and electrical fields; see Mazar 2009 pp .24-5. Tables 6 and 7 row 3 in ICNIRP 1998 p.511 and updated ICNIRP 2010 Table 4 p.827 specify the reference levels at extremely low frequencies (ELF) 50-60 Hz; much lower RF than the broadcasting and cellular radiations.

[7] See the Institute of Electrical and Electronic Engineers IEEE previous standard (Std), ANSI/IEEE C95.1-2006 section *1.3 Introduction*.

emission is involuntary. Chauncey Starr (1969 pp. 1232-8) proposed three tentative laws providing a quantitative instrument:

- The first law (the public is willing to accept voluntary risks) explains that the persons fighting against the cellular towers do nevertheless use cellular phones; since individuals are freely allowed to incur danger that threatens only themselves;
- The second law (the acceptability of risks appears to be roughly proportional to the real and perceived benefits) probably explains the positive perception of cellular activity in the Scandinavian countries (benefits to industry); and
- The third law (the acceptable level of risk is inversely related to the number of persons exposed to that risk) emphasises administrations' concern, regarding more than 8 billion users of cellular phones and millions of base-stations worldwide.

The global interest of public and Administration boosts international activities. The ITU Plenipotentiary Conference PP-18, which is the top policy-making body of the International Telecommunication Union (ITU), updated Resolution 176 (Rev. Busan, 2014) ‘Measurement and assessment concerns related to human exposure to electromagnetic fields’. The Question 7/2 “Strategies and policies concerning human exposure to EMF” Final Report (19 March 2021) of ITU-D Study Group 2 from the 7th study period (2017-2021) is significant.

9.2.3 *Risks from RF Exposure; the thermal damage*

Standards for non-ionizing radiation (NIR) exposure limits[8] are the formal instruments taken by governments to limit both the occurrence and the resulting consequences from potentially risky exposures to EMF generated by radiating emitters. Radiological electromagnetic standards 'race to the bottom' in reducing thresholds, *i.e.*, in 1995 the European committee for electrotechnical standardisation (CENELEC) established the European limit to the EMF power-density level[9] 9 W/m^2, at 900 MHz, and since June 2000 the European Commission (EC) adopted the ICNIRP 1998 (and ICNIRP 2020) level of (f(MHz)/200=) 4.5 W/m^2. Before the 21st century, emissions from wireless terminals of less than 7 Watts were not controlled; in contrast, at present, a typical cellular handset (UMTS or LTE) transmitting at a maximum of 200 mW undergoes regulatory testing. More societal concerns, more awareness, less public tolerability to health risks and the precautionary-principle explain this more restrictive approach; the lower limits are also a result of media campaigns and some regulatory rivalry (the low exposure levels in Italy, for example).

Generally, there are two types of potentially adverse effects: thermal and non-thermal. Thermal effects are caused by a malfunction of the body's thermo-regulation system, when it becomes unable to regulate the raise of human tissue temperature (due to the heat absorbed by the EMF) over the body's core temperature (about 36.5°C). Non-thermal effects are produced by interaction mechanism between the EMF and biological tissues or system, at power-density levels that do not necessarily increase significantly the tissue temperature. ICNIRP (1998) restrictions are based on established and measurable health effects, *i.e.*, based only on thermal effects; as the potential adverse impact of the non-thermal effect has never been established and remains controversial. ICNIRP (2020) states about nerve stimulation 'the ICNIRP (2020) Guidelines replace the 100 kHz to 10 MHz EMF frequency range of the ICNIRP (2010) guidelines, the science pertaining to direct RF EMF effects on nerve stimulation and associated restrictions within the ICNIRP (2010) guidelines has not been reconsidered'.

ICNIRP (1998) *(*and ICNIRP (2020)*)* basic restrictions on biological and health effects above 10 MHz are derived from a body temperature rise of more than 1°C. 'This level of temperature increase results from exposure of individuals under moderate environmental conditions to a whole-body SAR of approximately 4 W/kg for a time duration of about 30 minutes. A whole-body average SAR of 0.4W/kg has therefore been chosen as the restriction that provides adequate protection for occupational exposure[10]. An additional safety factor of 5 is introduced for of the general public, resulting in an average whole-body SAR limit of 0.08 W/kg' (ICNIRP 1998 p.509). A factor of 50 provides adequate protection for exposure of the public (ICNIRP 2009 Statement p.257).

[8] Recommendation ITU-T 2020 K.70 provides this 3.1.1 definition for NIR exposure limits 'values of the basic restrictions or reference levels acknowledged, according to obligatory regulations, as the limits for the permissible maximum level of the human exposure to the electromagnetic fields'.

[9] The former UK national radiological protection board (NRPB; was incorporated in the health protection agency (HPA) on 1 Apr 05) limited the power-density level of human-hazards (NRPB 1993 volumes 4 and 5) in the GSM900 band to **8.2** higher than the present ICNIRP 2020 and European threshold. Adopting the 'NRPB 2004: Recommendation 131' in the UK today, the emissions from cellular base stations meet the ICNIRP 1998 guidelines for public exposure. See also Recommendation ITU-R BS.1698 p.67 Table 9, which compares the power-density levels from the three renowned institutions.

[10] ICNIRP 1998 p.508 details: 'The occupationally exposed population consists of adults who are generally exposed under known conditions and are trained to be aware of potential risk and to take appropriate precautions. By contrast, the general public comprises individuals of all ages and of varying health status, and may include particularly susceptible groups or individuals'.

9.2.4 *Risks from RF Exposure: handheld devices*

The general public receives the highest exposure from handheld devices such as mobile phones, which deposit most of the radio frequency (RF) energy in the brain and surrounding tissues. Typical exposures to the brain from handsets are several orders of magnitude higher than those from mobile-phone base stations on rooftops or from terrestrial television and radio stations. As far as exposure levels are concerned, a distinction is made between the fixed radiating transmitters of the base stations and the portable handsets. The far-field[11] exposure from fixed wireless stations relative to power-density (or field-strength) limits is practical to analyse (easily simulated and measured). On the other hand, the handset is used in proximity to the user's body, meaning that the body in conjunction with the handset design have a strong impact on the RF-EMF in the near-field[12]. The Specific Absorption Rate (SAR)[13] relates to the internal electric field and by extension the temperature rise due to the EMF, mainly defines the threshold limits for sources used close to the body, including handsets and notebooks.

Manufacturers follow international compliance testing standards, to ensure that when tested the device operating at maximum power will comply with relevant international or national limits. The handset is working in full output power in the most conservative conditions (obstacles or long distance to base station), and in minimum output power in the best connection conditions (line of sight propagation and close to the base station). The maximum SAR level for different mobile phones varies according to technology and many other factors, for example, SAR is also influenced by technical parameters such as the antenna used and its placement within the device.

[11] Based on Rec ITU-T K.61, Rec K.91 defines far-field as "that region of the field of an antenna where the angular field distribution is essentially independent of the distance from the antenna. In the far-field region, the field has predominantly a plane-wave character, *i.e.*, locally uniform distribution of electric field strength and magnetic field strength in planes transverse to the direction of propagation".

[12] Based on Rec ITU-T K.52, Rec K.91 defines near-field as "the near-field region exists in the proximity to an antenna or other radiating structure in which the electric and magnetic fields do not have a substantially plane-wave character but vary considerably from point to point".

[13] SAR is the time derivative of the incremental power absorbed by (dissipated in) an incremental mass; it is expressed in W/kg. See also Recommendation (Rec) ITU-T K.52.

9.3 International Exposure Limits; ICNIRP Guidelines and IEEE Standard

9.3.1 *ICNIRP Guidelines (2010) and (2020) in force*

9.3.1.1 Developing ICNIRP Guidelines (2020)[14]

1. How ICNIRP (2020) Guidelines were done: identify scientific data on effects of exposure, determine effects considered both adverse to humans and scientifically substantiated, identify minimum exposure level needed to produce harm, apply reduction factors and larger for general public than for workers. This results in exposure restrictions with a large margin of safety.
2. The scientific basis: major reviews and original papers: only adverse health effects through nerve stimulation (up to ~10 MHz, limits from 2010 guidelines) and heating (from ~100 kHz). There is no evidence for cancer, electromagnetic hypersensitivity, infertility or other health effects. The identified adverse health effects are deep body temperature increase above 1 °C and tissue temperature above 41 °C.
3. Physics and Temperature: different quantities used to correlate with temperature depending on frequency and duration of exposure. For example, for continuous local exposures: absorbed energy rate (SAR) at lower frequencies, absorbed power density at higher frequencies.

9.3.1.2 The Tables and Figures of ICNIRP (2020)

This section details the most relevant Tables (1, 5 and 6) of ICNIRP (2020). The Figures (not from the Guidelines) depict values and comparisons. Underlined text indicates the significant parameter (also in IEEE 95.1 Tables). Comparisons to ICNIRP 2010 (for frequencies lower than 100 kHz) are inserted.

Table 9.1: (ICNIRP Table 1) ICNIRP (2020) Quantities and corresponding SI[15] units used

Quantity	**Symbol[a]**	**Unit**
Absorbed energy density	U_{ab}	joule per square meter (J m^{-2})
Incident energy density	U_{inc}	joule per square meter (J m^{-2})
Plane-wave equivalent incident energy density	U_{eq}	joule per square meter (J m^{-2})
Absorbed power density	S_{ab}	watt per square meter (W m^{-2})
Incident power density	S_{inc}	watt per square meter (W m^{-2})
Plane-wave equivalent incident power density	S_{eq}	watt per square meter (W m^{-2})
Induced electric field strength	E_{ind}	volt per meter (V m^{-1})
Incident electric field strength	E_{inc}	volt per meter (V m^{-1})
Incident magnetic field strength	H_{inc}	ampere per meter (A m^{-1})

[14] Retrieved from ICNIRP website https://www.icnirp.org/en/activities/news/news-article/rf-guidelines-2020-published.html

[15] the International System of Units (SI)

Quantity	**Symbol[a]**	**Unit**
Specific energy absorption	SA	joule per kilogram (J kg^{-1})
Specific energy absorption rate	SAR	watt per kilogram (W kg^{-1})
Electric current	I	ampere (A)
Frequency	*f*	hertz (Hz)
Time	*t*	second (s)

[a] *Italicized* symbols represent variables; quantities are described in scalar form, because direction is not used to derive the basic restrictions or reference levels.

Table 9.2 and Table 9.3 (Tables 5 and 6 respectively from ICNIRP 2020) detail reference levels.

Table 9.2: (ICNIRP Table 5) Reference levels for exposure, averaged over 30 minutes and the whole body, to electromagnetic fields from 100 kHz to 300 GHz (unperturbed rms values)

Exposure scenario	**Frequency range**	**Incident E-field strength; E_{inc} (V m^{-1})**	**Incident H-field strength; H_{inc} (A m^{-1})**	**Incident power density; S_{inc} (W m^{-2})**
Occupational	0.1 – 30 MHz	$660/f_M^{0.7}$	$4.9/f_M$	NA
	>30 – 400 MHz	61	0.16	10
	>400 – 2000 MHz	$3f_M^{0.5}$	$0.008f_M^{0.5}$	$f_M/40$
	>2 – 300 GHz	NA	NA	*50*
General Public	0.1 – 30 MHz	$300/f_M^{0.7}$	$2.2/f_M$	NA
	>30 – 400 MHz	27.7	0.073	2
	>400 – 2000 MHz	$1.375f_M^{0.5}$	$0.0037f_M^{0.5}$	$f_M/200$
	>2 – 300 GHz	NA	NA	10

Notes (from ICNIRP 2020):
1. 'NA' signifies 'not applicable' and does not need to be taken into account when determining compliance.
2. f_M is frequency in MHz.
3. S_{inc}, E_{inc} and H_{inc} are to be averaged over 30 minutes, over the whole-body space. Temporal and spatial averaging of each of E_{inc} and H_{inc} must be conducted by averaging over the relevant square values (see Eqn. 8 in Appendix A for details).
4. For frequencies of 100 kHz to 30 MHz, regardless of the far-field/near-field zone distinctions, compliance is demonstrated if neither E_{inc} or H_{inc} exceeds the above reference level values.
5. For frequencies of >30 MHz to 2 GHz: (a) within the far-field zone: compliance is demonstrated if either S_{inc}, E_{inc} or H_{inc}, does not exceed the above reference level values (only one is required); S_{eq} may be substituted for S_{inc}; (b) within the radiative near-field zone, compliance is demonstrated if either S_{inc}, or both E_{inc} and H_{inc}, does not exceed the above reference level values; and (c) within the reactive near-field zone: compliance is demonstrated if both E_{inc} and H_{inc} do not exceed the above reference level values; S_{inc} cannot be used to demonstrate compliance, and so basic restrictions must be assessed.
6. For frequencies of >2 GHz to 300 GHz: (a) within the far-field zone: compliance is demonstrated if S_{inc} does not exceed the above reference level values; S_{eq} may be substituted for S_{inc}; (b) within the radiative near-field zone, compliance is demonstrated if S_{inc} does not exceed the above reference level values; and (c) within the reactive near-field zone, reference levels cannot be used to determine compliance, and so basic restrictions must be assessed.

Table 9.3: (ICNIRP Table 6) Reference levels for local exposure, averaged over 6 minutes, to electromagnetic fields from 100 kHz to 300 GHz (unperturbed rms values)

Exposure scenario	**Frequency range**	**Incident E-field strength; E_{inc} (V m^{-1})**	**Incident H-field strength; H_{inc} (A m^{-1})**	**Incident power density; S_{inc} (W m^{-2})**
Occupational	0.1 – 30 MHz	$1504/f_M^{0.7}$	$10.8/f_M$	NA
	>30 – 400 MHz	139	0.36	50
	>400 – 2000 MHz	$10.58 f_M^{0.43}$	$0.0274 f_M^{0.43}$	$0.29 f_M^{0.86}$
	>2 – 6 GHz	NA	NA	200
	>6 – <300 GHz	NA	NA	$275/f_G^{0.177}$
	300 GHz	NA	NA	100
General Public	0.1 – 30 MHz	$671/f_M^{0.7}$	$4.9/f_M$	NA
	>30 – 400 MHz	62	0.163	10
	>400 – 2000 MHz	$4.72 f_M^{0.43}$	$0.0123 f_M^{0.43}$	$0.058 f_M^{0.86}$
	>2 – 6 GHz	NA	NA	40
	>6 – 300 GHz	NA	NA	$55/f_G^{0.177}$
	300 GHz	NA	NA	20

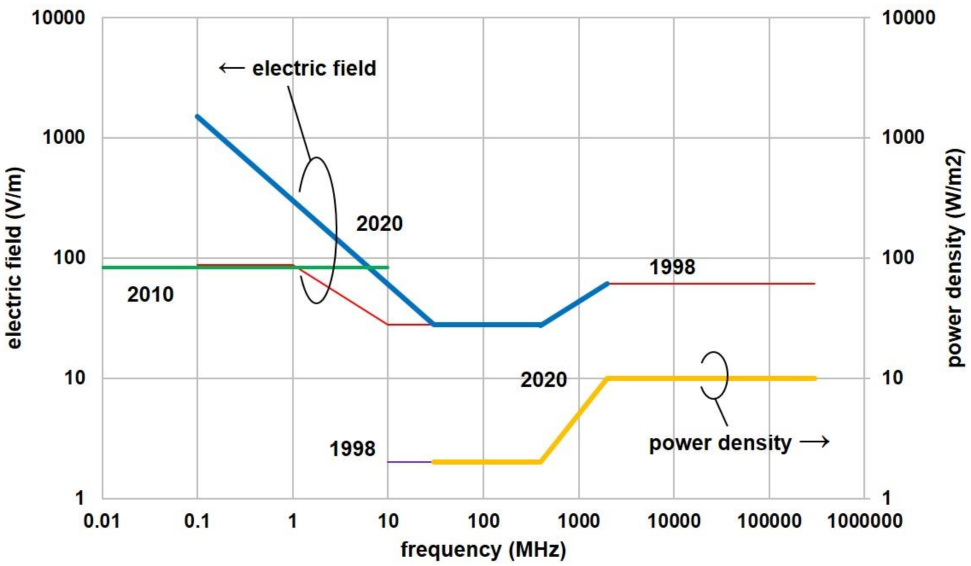
Notes (from ICNIRP 2020):

1. 'NA' signifies 'not applicable' and does not need to be taken into account when determining compliance.
2. f_M is frequency in MHz; f_G is frequency in GHz.
3. S_{inc}, E_{inc} and H_{inc} are to be averaged over 6 minutes, and where spatial averaging is specified in Notes 6-7, over the relevant projected body space. Temporal and spatial averaging of each of E_{inc} and H_{inc} must be conducted by averaging over the relevant square values (see Eqn. 8 in Appendix A for details).
4. For frequencies of 100 kHz to 30 MHz, regardless of the far-field/near-field zone distinctions, compliance is demonstrated if neither peak spatial E_{inc} or peak spatial H_{inc}, over the projected whole-body space, exceeds the above reference level values.
5. For frequencies of >30 MHz to 6 GHz: (a) within the far-field zone, compliance is demonstrated if one of peak spatial S_{inc}, E_{inc} or H_{inc}, over the projected whole-body space, does not exceed the above reference level values (only one is required); S_{eq} may be substituted for S_{inc}; (b) within the radiative near-field zone, compliance is demonstrated if either peak spatial S_{inc}, or both peak spatial E_{inc} and H_{inc}, over the projected whole-body space, does not exceed the above reference level values; and (c) within the reactive near-field zone: compliance is demonstrated if both E_{inc} and H_{inc} do not exceed the above reference level values; S_{inc} cannot be used to demonstrate compliance; for frequencies >2 GHz, reference levels cannot be used to determine compliance, and so basic restrictions must be assessed.
6. For frequencies of >6 GHz to 300 GHz: (a) within the far-field zone, compliance is demonstrated if S_{inc}, averaged over a square 4-cm^2 projected body surface space, does not exceed the above reference level values; S_{eq} may be substituted for S_{inc}; (b) within the radiative near-field zone, compliance is demonstrated if S_{inc}, averaged over a square 4-cm^2 projected body surface space, does not exceed the above reference level values; and (c) within the reactive near-field zone, reference levels cannot be used to determine compliance, and so basic restrictions must be assessed.
7. For frequencies of >30 GHz to 300 GHz, exposure averaged over a square 1-cm^2 projected body surface space must not exceed twice that of the square 4-cm^2 restrictions.

The following four ICNIRP Figures appear in the 'Differences Between the ICNIRP (2020) and Previous Guidelines', which are clearer, but could not be included in the *Health Physics* publication. The units of the two y-axes (*i.e.*, electric field and power density) are independent of each other. Local exposure reference levels were not given in the ICNIRP (1998) and ICNIRP (2010) guidelines. The reference-levels of ICNIRP (2020) stop electric-field at frequencies above 2 000 MHz, and start power-density above 30 MHz, see ICNIRP Tables 5 and 6, and the four following Figures.

The four following Figures[16] have commons; the whole-body levels are for 30 min averaging and the local-levels for 6 min. To focus the reader and depict the differences, the titles are simplified: 'from 100 kHz to 300 GHz frequency range' is not repeated and the specifics are underlined:

Figure 9.2 Whole body average reference levels for the general public for the ICNIRP (1998), ICNIRP (2010) and ICNIRP (2020) guidelines



Introduction of ICNIRP 2020 states 'This publication replaces the 100 kHz to 300 GHz part of the ICNIRP (1998) radiofrequency guidelines, as well as the 100 kHz to 10 MHz part of the ICNIRP (2010) low-frequency guidelines.' With decreasing frequencies, at some frequency the 2010 reference levels become more restrictive than the 2020 ones. For the general public, comparing Table 5 of ICNIRP 2020, where the E-field averaged over 30 min and the whole body for 0.1– 30 MHz is $300/fM^{0.7}$, to Table 4 of ICNIRP 2010 where the E-field is 83 V/m for frequencies up to 10 MHz, the intersection is at 6.27 MHz ($300/fM^{0.7}$ $=300/6.27^{0.7}$=83 V/m). Thus, below 6.27 MHz, ICNIRP 2010 is more restrictive than ICNIRP 2020. As ICNIRP 1998 is obsolete, ICNIRP 2010 is most relevant for frequencies 100 kHz and lower, at 100 kHz and below, the reference levels for the general public are lowered from 87 V/m (ICNIRP 1998) to 83 V/m (ICNIRP 2010).

[16] retrieved on 30 December 2020 from https://www.icnirp.org/en/differences.html

Figure 9.3 ICNIRP (2020) reference levels for the general public applying to local exposures ≥6 min

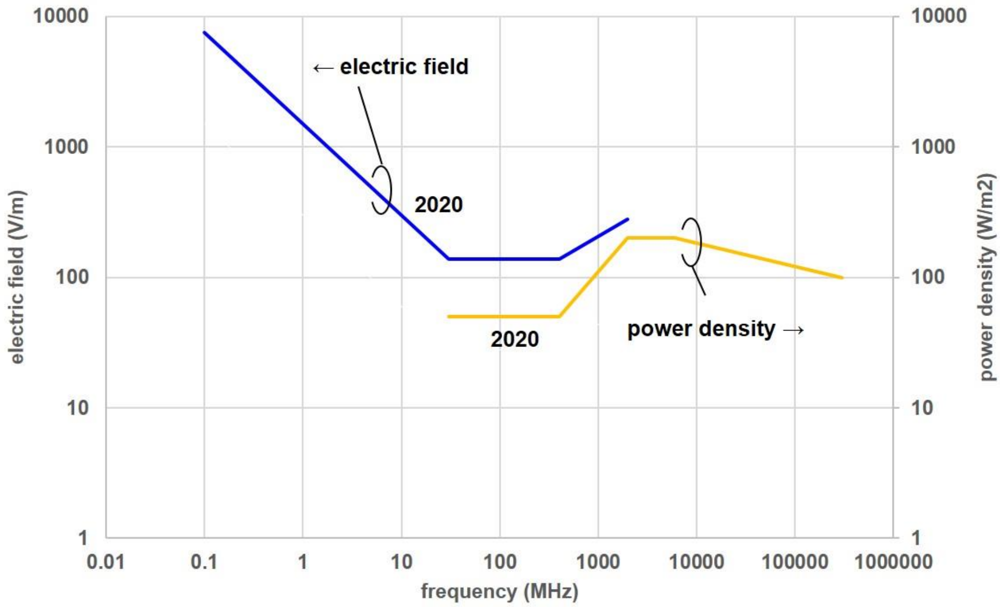


Figure 9.4 Whole body average reference levels for workers for the ICNIRP (1998), ICNIRP (2010) and ICNIRP (2020) Guidelines

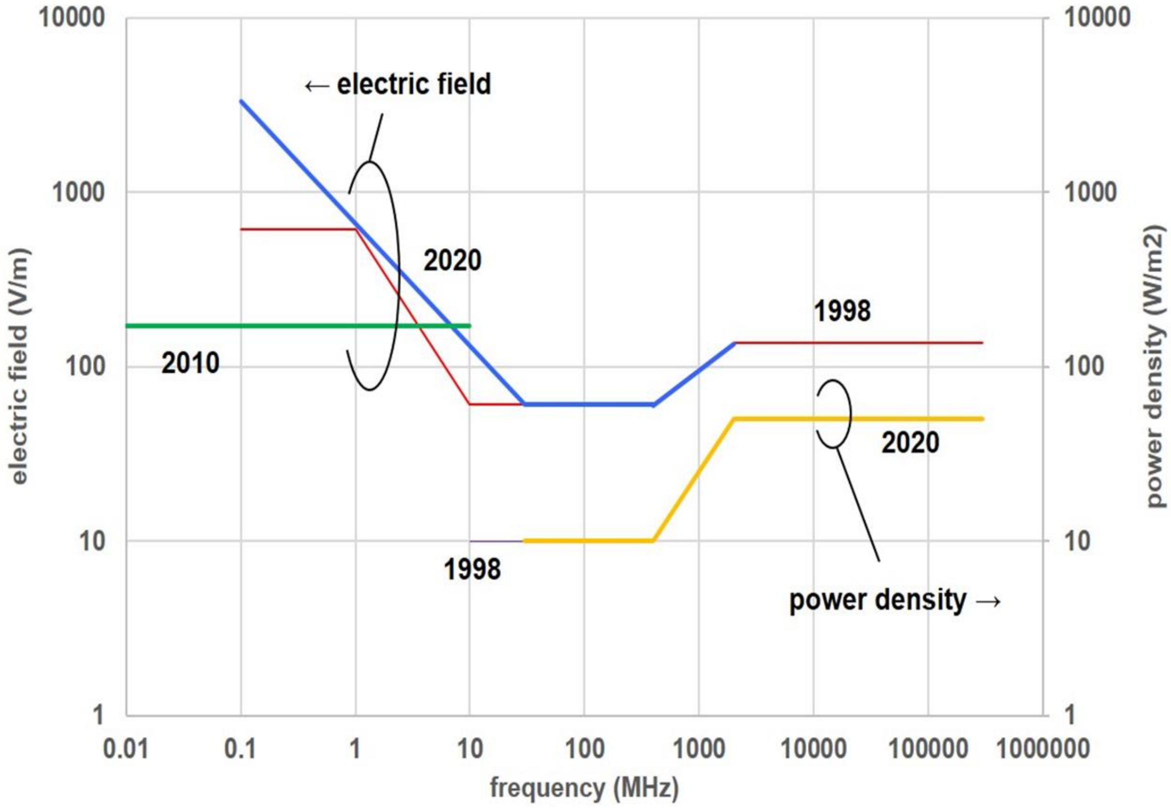
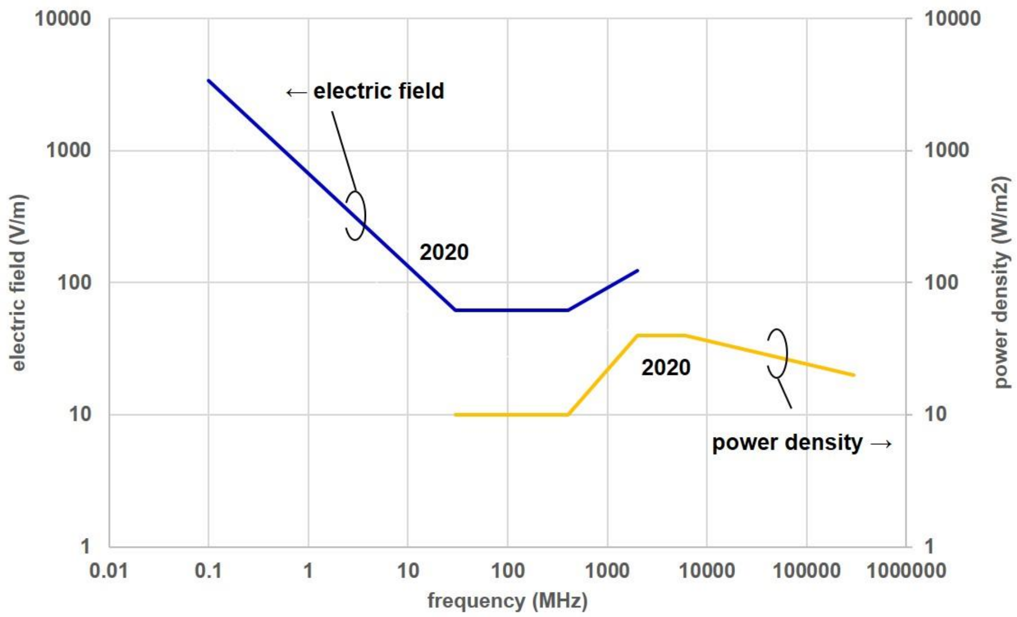


Figure 9.5 Reference levels for workers applying to local exposures ≥6 min for the ICNIRP (2020) Guidelines



The following Table[17] provides an overview of basic restrictions contained in the ICNIRP (2020) Guidelines.

Table 9.4: ICNIRP (2020) Guidelines in brief; Basic Restrictions

Parameter	Frequency range	ΔT	Spatial averaging	Temporal averaging	Health effect level	Reduction factor	Workers	Reduction factor	General public
Core ΔT	100 kHz-300 GHz	1°C	WBA (whole body average)	30 min	4 W/kg	10	0.4 W/kg	50	0.08 W/kg
Local ΔT (Head & Torso)	100 kHz-6 GHz	2°C	10 g	6 min	20 W/kg	2	10 W/kg	10	**2 W/kg**
Local ΔT (Limbs)		5°C	10 g	6 min	40 W/kg	2	20 W/kg	10	4 W/kg
Local ΔT (Head & Torso, Limbs)	>6-300 GHz 30-300 GHz	5°C	4 cm^2 1 cm^2	6 min 6 min	200 W/m^2 400 W/m^2	2	100 W/m^2 200 W/m^2	10	20 W/m^2 40 W/m^2

[17] The following Table and three Figures have been prepared by the Author

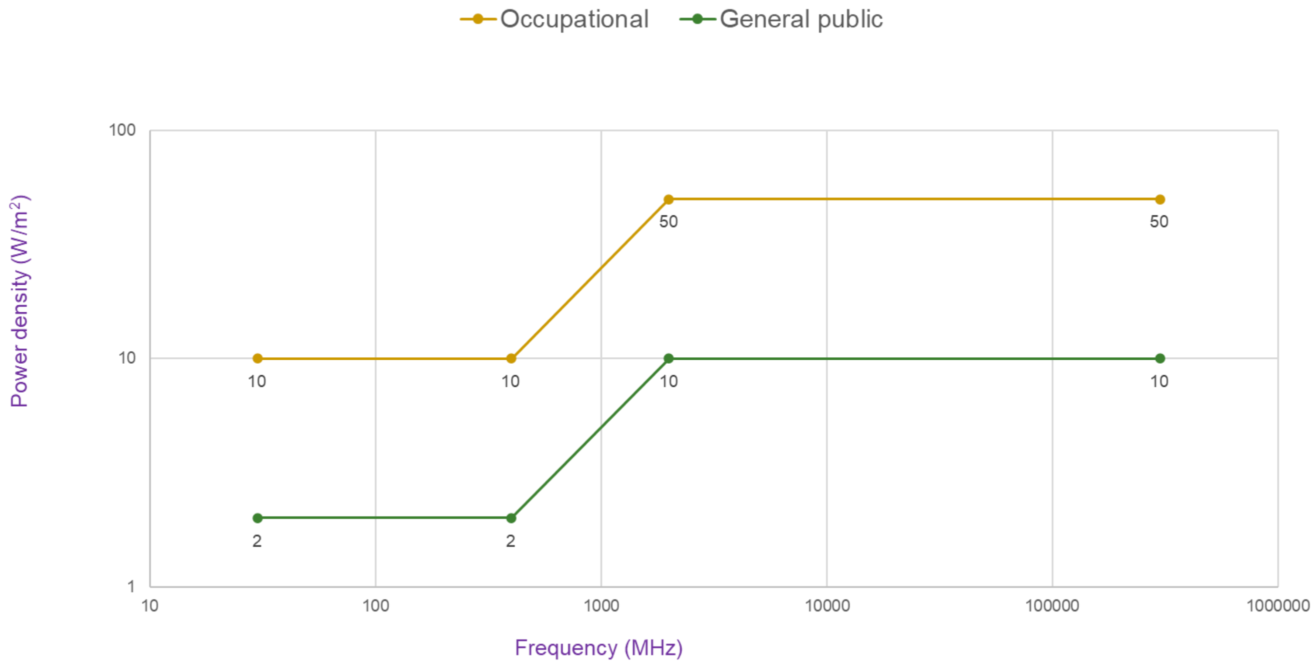
ICNIRP (2010) and ICNIRP (2020) are based on two different biological mechanisms, and averaging is diverse:

- nerve stimulation- instantaneous below 10 MHz;
- thermal effect, produced by power over time (for frequencies above 100 kHz).

Below 100 kHz, ICNIRP (2010) should be applied. Between 100 kHz and 10 MHz both mechanisms may exist, in that case, the more **stringent** value for every frequency should be followed. Moreover, ICNIRP (2020) Table 8 states (pay attention to the bold text) "*reference levels for **local exposure** to EMFs from 100 kHz to 10 MHz (unperturbed rms values), for **peak values**, the occupational limit is 170 V/m and the general public is 83 V/m*.".
As between 100 kHz and 10 MHz, the more stringent value for every frequency should be followed, the following figure depicts ICNIRP (2020) exposures, truncated where ICNIRP (2010) exposures apply (below ≈7 MHz): for 'occupational' below **6.94 MHz** (**170 V/m**) ICNIRP (2010) Table 3, and for the general public below **6.27 MHz (83 V/m**), ICNIRP (2010) Table 4. However, this does not mean that the higher (thermal) reference levels in ICNIRP 2020 Table 5 are never relevant for frequencies below around 7 MHz. When there are other, higher frequency components present and summation is required to carry out an assessment of the cumulative effect of these multiple frequency components, then the Table 5 Reference levels will be relevant for all frequencies over 100 kHz; see Figure 9.7.

The following two figures[18] depict the differences between the ICNIRP (2020) **field-strength** and **power-density** exposure levels of **occupational** and **general-public** exposure, averaged over **30 min** and the **whole body**. The power-density ratio of 5 in ICNIRP (2020) Table 5 (e.g., at 30 – 400 MHz, Watts ratio 50/10) results in V/M ratio 61.0/27.7 = 2.2 ≈ √5.

Figure 9.6 Comparing ICNIRP (2020) Table 5, power-density for occupational and general-public exposures 30 MHz–300 GHz, averaged over 30 min and the whole body



[18] Based on Figures 7 and 8 (source Dr. Haim Mazar) in Background Paper, ITU Regional Forum for Europe: 5G, Strategies, Policies, and Implementation, October 2020

As between 100 kHz and 10 MHz, the stringent value for every frequency should be followed, the following two figures depict ICNIRP (2020) exposures, truncated where ICNIRP (2010) exposures apply[19].

Figure 9.7 Comparing ICNIRP (2020) Table 5, field-strength for occupational and general-public exposure, 0.1 MHz–2 000 MHz, averaged over 30 minutes and the whole-body

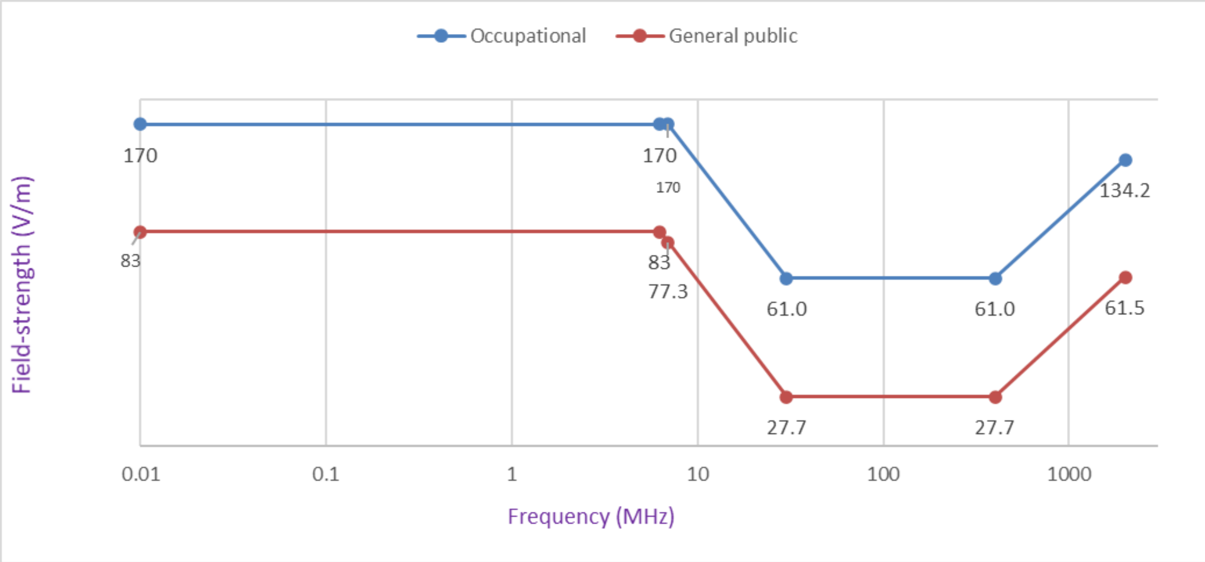
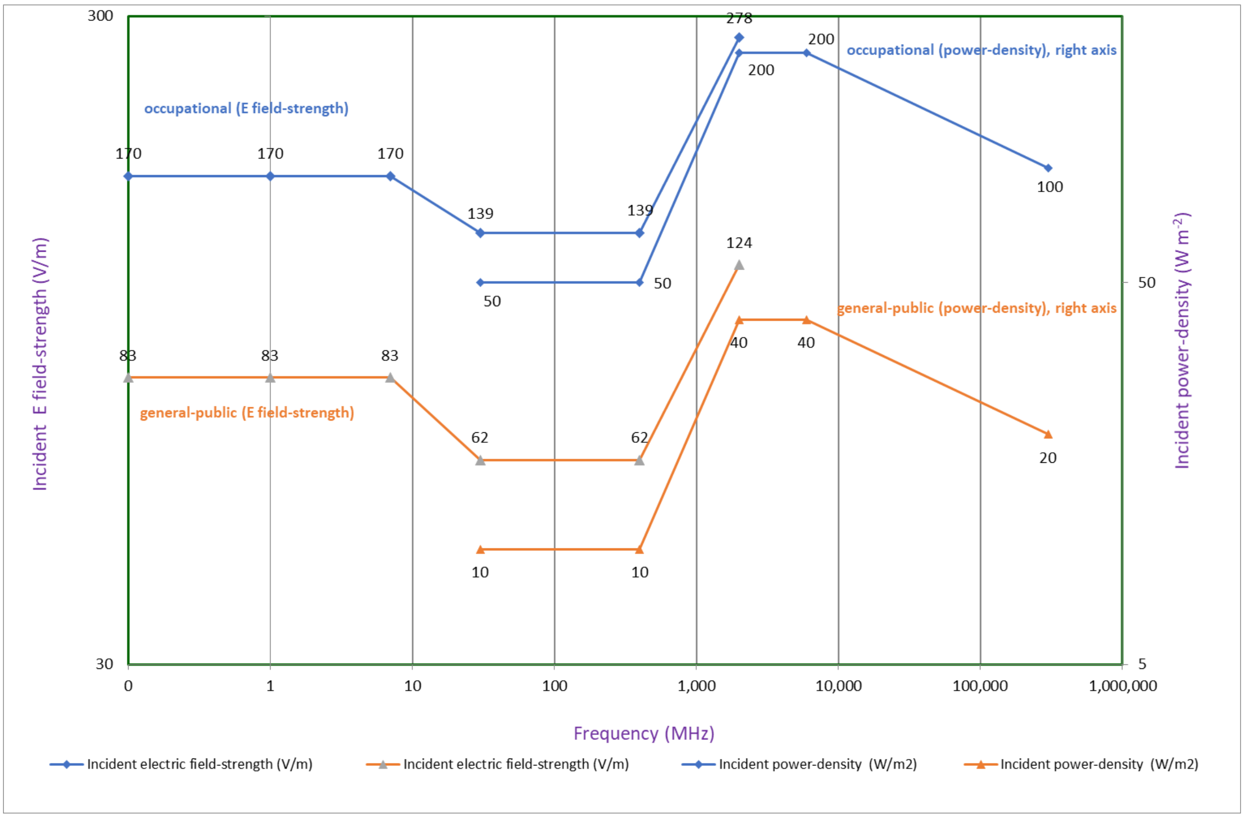


Figure 9.8 Comparing occupational and general-public exposures in ICNIRP (2020) Table 6, incident electric field-strength and power-density; local-exposure, averaged over 6 minutes



Note: the units of the two y-axes (*i.e.*, incident electric field-strength and power-density) are independent of each other.

[19] Limited below ≈7 MHz by ICNIRP (2010) for 'occupational' below **6.94 MHz** (**170 V/m**) ICNIRP (2010) Table 3, and for the general public below **6.27 MHz (83 V/m)**, ICNIRP (2010) Table 4

9.3.2 *IEEE C95.1-2019*

9.3.2.1 Reference levels: safety factors applying 100 kHz- 6 GHz; Thermal Effects[20]

- Whole body averaged (WBA)
  Behavioural effects in animals over many frequencies, threshold at 4 W/kg, before dividing by:
  10x - 0.4 W/kg for upper tier (controlled environment)
  50x - 0.08 W/kg for lower tier (general public)
- Localized exposure (averaged in 10 g),
  Cataract observed in rabbits, threshold at 100 W/kg, before dividing by:
  10x - 10 W/kg for upper tier
  50x - 2 W/kg for lower tier
- SAR is averaged over 30 min for WBA exposure and 6 min for local exposure
- Epithelial power density through body surface is averaged over 6 min

9.3.2.2 Dosimetric Reference Limits and Exposure Reference Level[21]

The following two Tables specify Dosimetric Reference Limits (DRLs) below and above 6 GHz. No continuity at 6 GHz.

Table 9.5: C95.1-2019 (Table 5) – Dosimetric Reference Limits, DRLs (100 kHz to 6 GHz)

Conditions Persons in	**unrestricted environments SAR (W/kg)**[a]	**restricted environments SAR (W/kg)**[a]
Whole-body exposure	0.08	0.4
Local exposure[b] (head and torso)	2	10
Local exposure[b] (limbs and pinnae)	4	20

[a] SAR is averaged over 30 min for whole-body exposure and 6 min for local exposure.
[b] Averaged over any 10 g of tissue (defined as a tissue volume in the shape of a cube). The averaging volume of 10 g of tissue would be represented as a 10 cm3 cube (approximately 2.15 cm per side)

Table 9.6: C95.1-2019 (Table 6) – DRLs (6 GHz to 300 GHz)

Conditions	**Epithelial power density (W/m^2)**[a,b,c]	
	Persons in unrestricted Environments	**Persons permitted in restricted environments**
Body surface	20	100

[a] Epithelial power density through body surface is averaged over 6 min.
[b] Averaged over any 4 cm^2 of body surface at frequencies between 6 GHz and 300 GHz (defined as area in the shape of a square at surface of the body).
[c] Small exposed areas above 30 GHz: If the exposed area on the body surface is small (< 1 cm^2 as defined by −3 dB contours relative to the peak exposure), the epithelial power density is allowed to exceed the DRL values of Table 6 by a factor of 2, with an averaging area of 1 cm^2 (defined as area in the shape of a square at the body surface).

[20] See IEEE C95.1-2019 p. 57
[21] See IEEE C95.1-2019, Tables 5 to 8, Figures 3 and 4

The following Tables do not provide the electric and magnetic field-strengths above 400 MHz[22].

The following Table details Exposure Reference Level (ERLs) for whole-body exposure of persons in unrestricted environments, averaging time 30 minutes.

Table 9.7: C95.1-2019 (Table 7) – Exposure Reference Level, ERLs (100 kHz to 300 GHz)

<table>
<tr><th rowspan="2">Frequency range (MHz)</th><th rowspan="2">Electric field Strength (E)[a,b,c] (V/m)</th><th rowspan="2">Magnetic field strength (H)[a,b,c] (A/m)</th><th colspan="2">Power density (S)[a,b,c] (W/m^2)</th></tr>
<tr><th>S_E</th><th>S_H</th></tr>
<tr><td>0.1 to 1.34</td><td>614</td><td rowspan="2">$16.3/f_M$</td><td>1000</td><td rowspan="2">$100\ 000/ f_M^2$</td></tr>
<tr><td>1.34 to 30</td><td>$823.8/f_M$</td><td>$1800 / f_M^2$</td></tr>
<tr><td>30 to 100</td><td rowspan="2">27.5</td><td>$158.3/f_M^{1.668}$</td><td>2</td><td>$9\ 400\ 000 / f_M^{3.336}$</td></tr>
<tr><td>100 to 400</td><td>0.0729</td><td colspan="2">2</td></tr>
<tr><td>400 to 2000</td><td colspan="2"></td><td colspan="2">$f_M/200$</td></tr>
<tr><td>2000 to 300 000</td><td colspan="2"></td><td colspan="2">10</td></tr>
</table>

Note—S_E and S_H are plane-wave-equivalent power density values, based on electric or magnetic field strength respectively, and are commonly used as a convenient comparison with ERLs at higher frequencies and are sometimes displayed on commonly used instruments.

[a] For exposures that are uniform over the dimensions of the body, such as certain far-field plane-wave exposures, the exposure field strengths and power densities are compared with the ERLs in IEEE 95.1 Table 7. For more typical non-uniform exposures, the mean values of the exposure fields, as obtained by spatially averaging the plane-wave-equivalent power densities or the squares of the field strengths, are compared with the ERLs in Table 7.

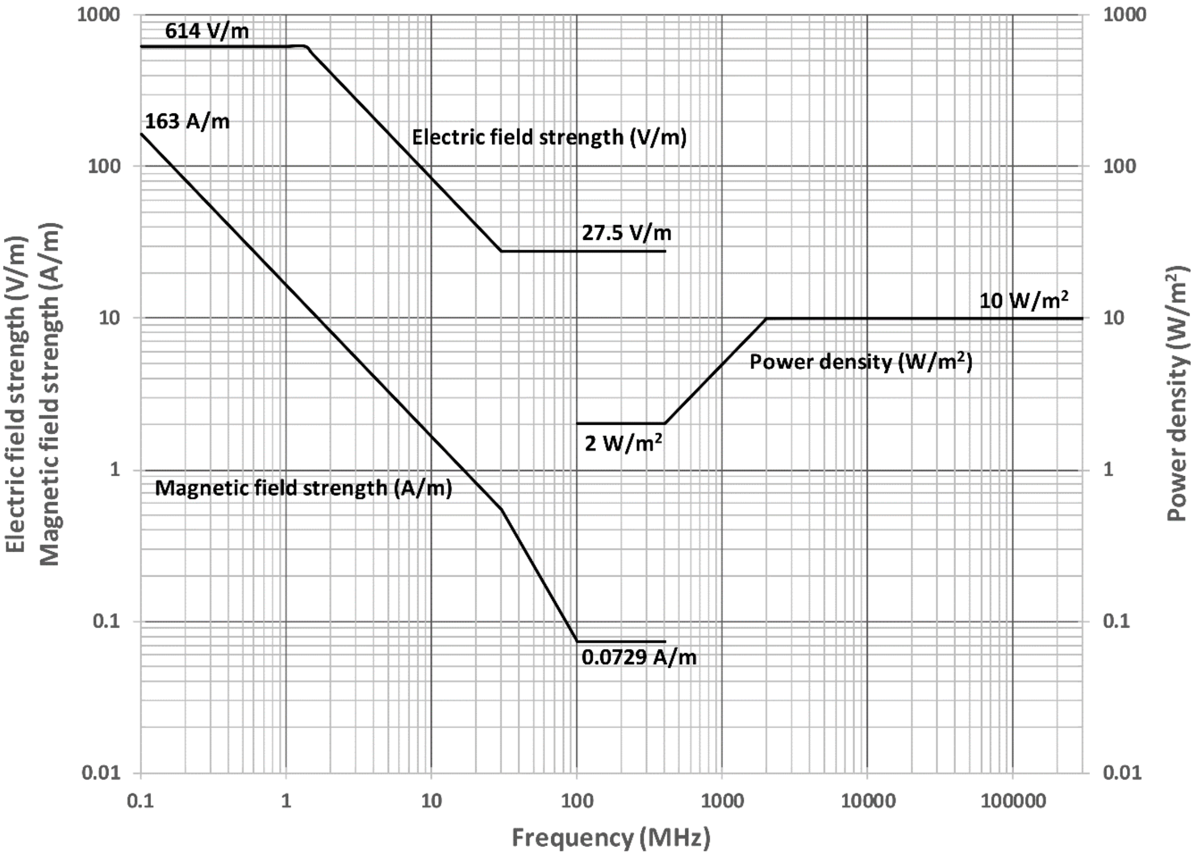
[b] f_M is the frequency in MHz.

[c] The E, H, and S values are those rms values unperturbed by the presence of the body.

[22] The reference-levels of ICNIRP (2020) stop electric-field at frequencies above 2 000 MHz, and start power-density above 30 MHz, see ICNIRP Tables 5 and 6.

The following Figure depicts C95.1-2019 Figure 3—Graphical representations of the ERLs in Table 7 of IEEE Standard, electric and magnetic fields and plane-wave-equivalent power density—Persons in **unrestricted** environments.

Figure 9.9 C95.1-2019 (Figure 3) EMFs and power density—persons permitted in unrestricted environments



Important to note, not at the IEEE 95.1 standard, that at frequencies below 30 MHz, the wavelength is longer than 10 m. There is no resonance with our body (shorter than 2 m.). We are not an obstacle to the signal, and low part of the RF energy enters to our body.

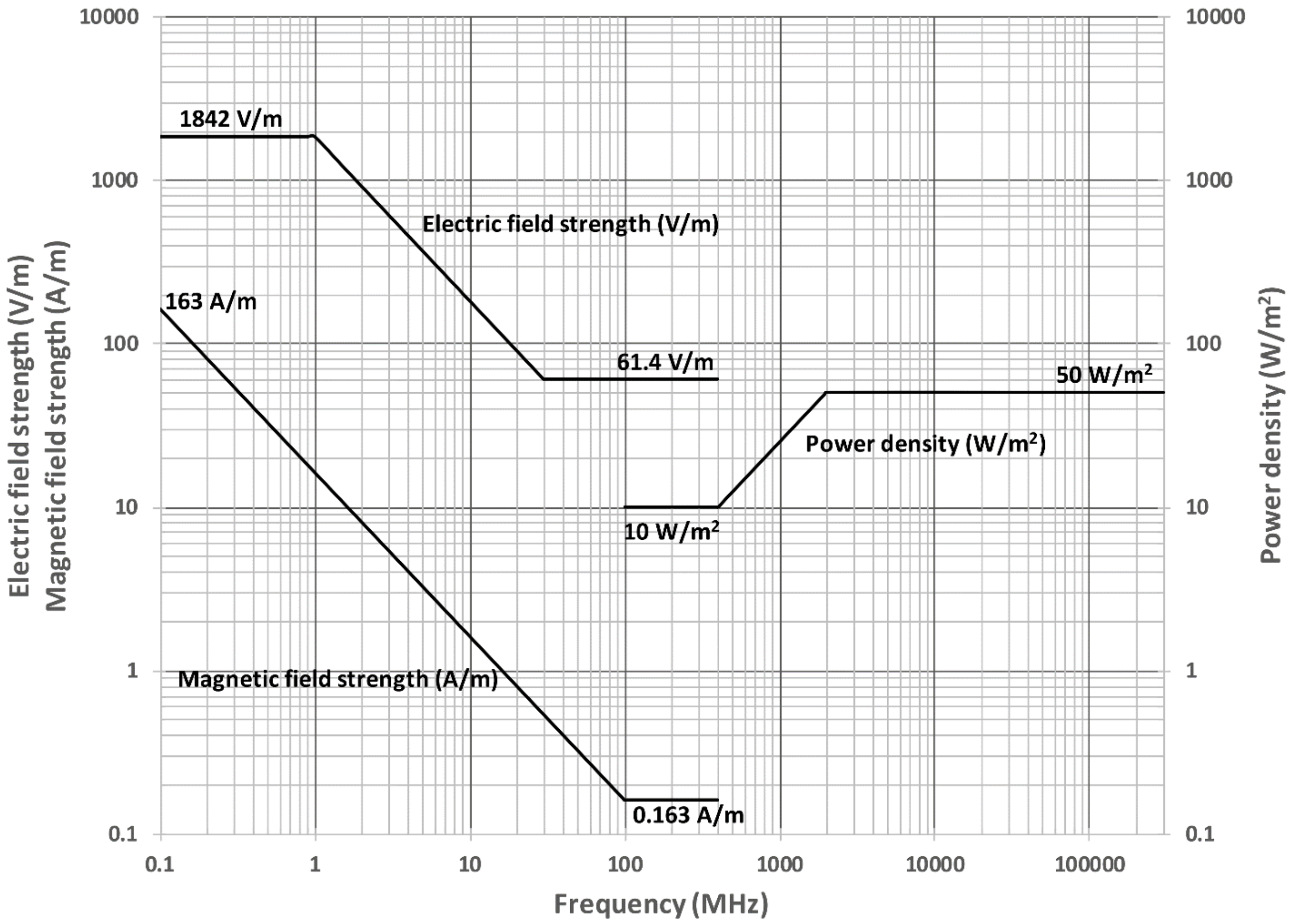
The following Table details IEEE C95.1-2019 Table 8—ERLs for whole-body exposure of persons permitted in **restricted** environments (100 kHz to 300 GHz), the averaging time is 30 minutes.

Table 9.8: C95.1-2019 (Table 8) – ERLs in restricted environments (100 kHz to 300 GHz)

<table>
<tr><th>Frequency range (MHz)</th><th>Electric field Strength $(E)^{a,b,c}$ (V/m)</th><th>Magnetic field strength $(H)^{a,b,c}$ (A/m)</th><th colspan="2">Power density $(S)^{a,b,c}$ (W/m^2)</th></tr>
<tr><td rowspan="2">0.1 to 1.0</td><td rowspan="2">1842</td><td rowspan="4">16.3/f_M</td><td>S_E</td><td>S_H</td></tr>
<tr><td>9 000</td><td rowspan="3">100 000 f_M^2</td></tr>
<tr><td>1.0 to 30</td><td>1842/f_M</td><td>9000 / f_M^2</td></tr>
<tr><td>30 to 100</td><td rowspan="2">61.4</td><td>10</td></tr>
<tr><td>100 to 400</td><td>0.163</td><td colspan="2">10</td></tr>
<tr><td>400 to 2000</td><td colspan="2"></td><td colspan="2">f_M/40</td></tr>
<tr><td>2000 to 300 000</td><td colspan="2"></td><td colspan="2">50</td></tr>
</table>

The following Figure depicts C95.1-2019 Figure 4: Graphical representations of the ERLs in IEEE (Table 8) for electric and magnetic fields and plane-wave-equivalent power density – Persons permitted in **restricted** environments.

Figure 9.10 C95.1-2019 (Figure 4) EMFs and power density—persons permitted in restricted environments



9.3.3 *Compare and Contrast ICNIRP 1998, IEEE 95-1 2019 and ICNIRP 2020*

9.3.4 *IEEE C95.1 2019 and ICNIRP 2020 Guidelines are largely harmonized*

The ICNIRP Guidelines (1998, and 2020) and the IEEE Standard (2019) separate between persons in unrestricted environments (general-public) and persons permitted in restricted environments (occupational). The exposure levels of ICNIRP 2020 and the IEEE Standard are largely harmonized, and the power-density limits whole-body levels above 30 MHz are identical!

– Localised SAR limits in the Head/Torso equals 2 W/kg for general-public and 10 W/kg for occupational.

– Whole-body average SAR limit equals 0.08 W/kg for general-public and 0.4 W/kg for occupational.

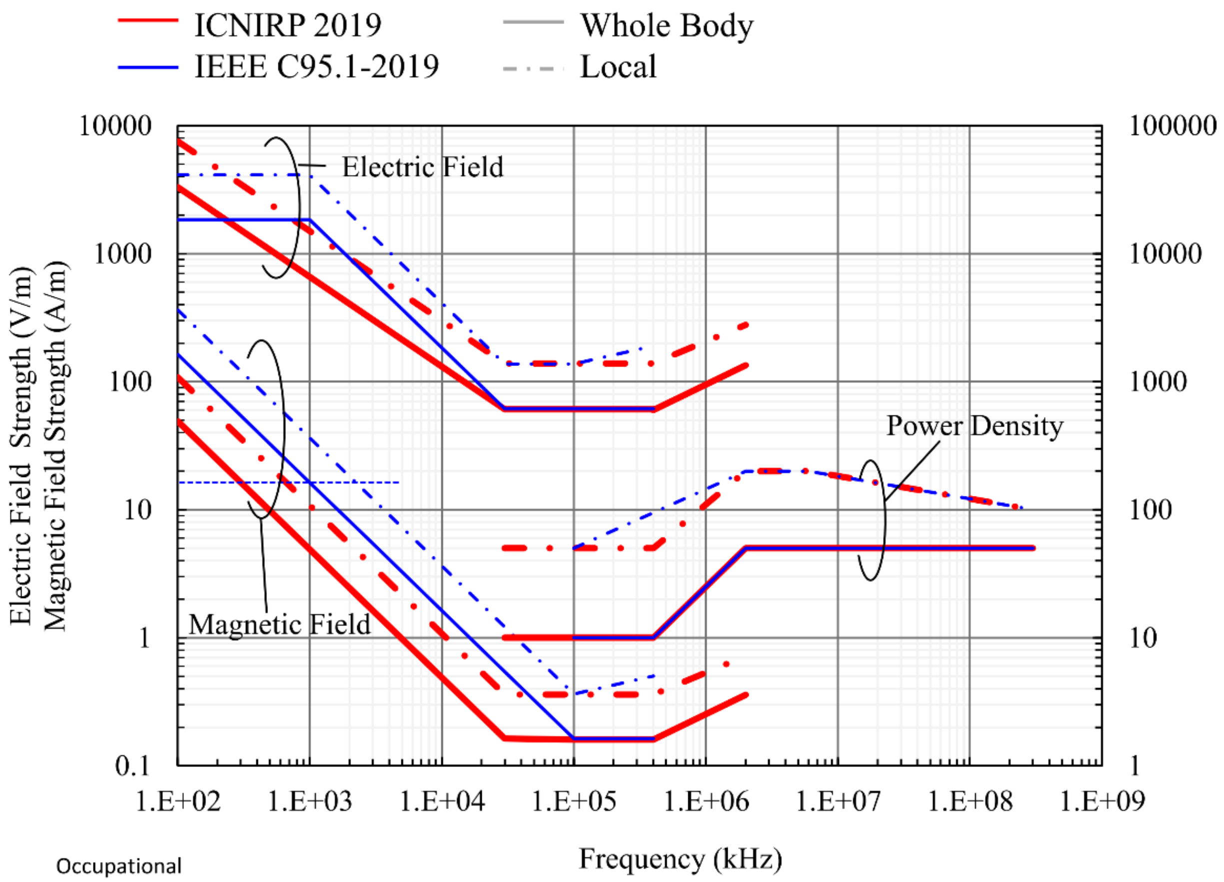
– Exposure power-density reference-levels equal at:
  - 30 to 400 MHz: 2 W/m^2 for general-public and 10 W/m^2 for occupational;
  - 400 to 2 000 MHz: f_M/200 W/m^2 for general-public and f_M/40 W/m^2 for occupational;

- 2 000 to 300 000 MHz: 10 W/m^2 for general-public and 50 W/m^2 for occupational.

The following three Figures illustrate that IEEE C95.1 (2019) and ICNIRP (2020) Guidelines are **largely harmonized**.

The following Figure[23] compares the Reference Limits (RLs) between ICNIRP and IEEE for **occupational-exposure**.

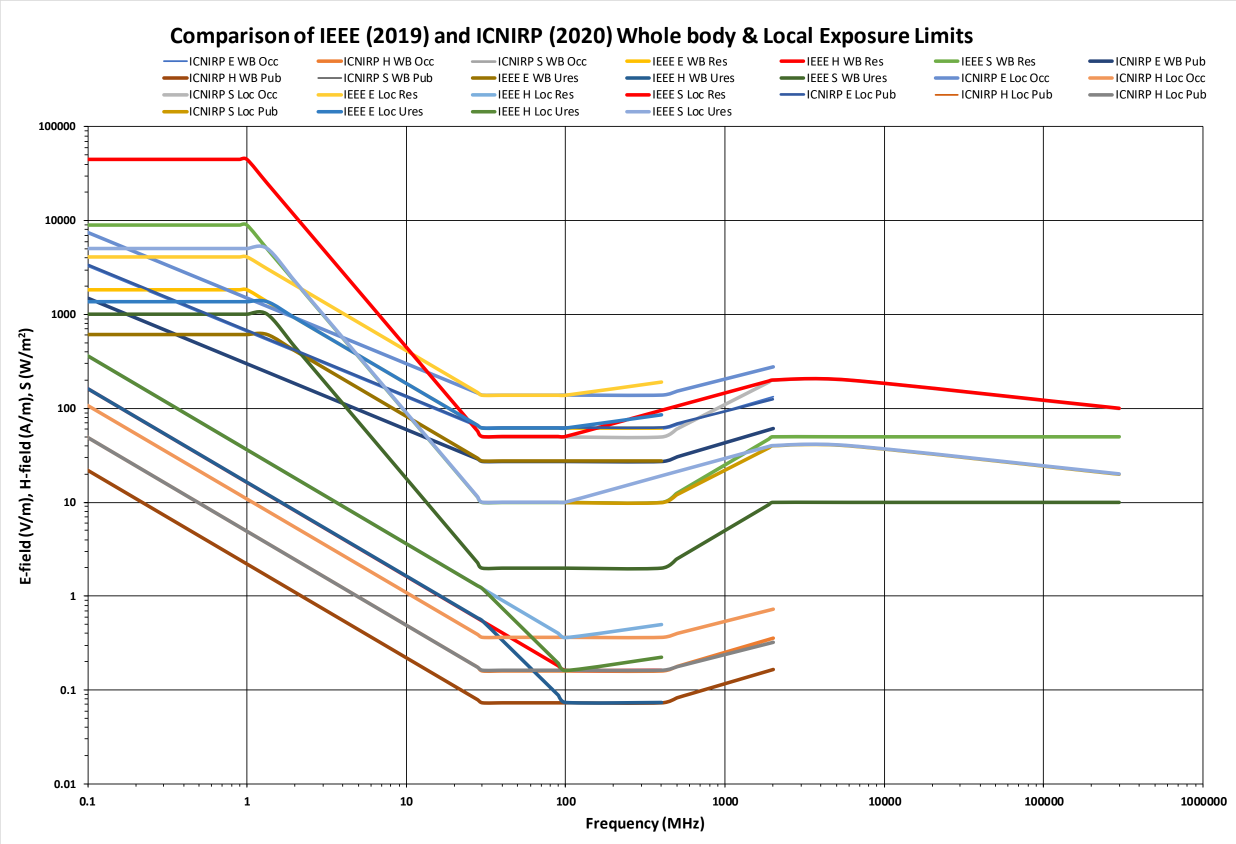
Figure 9.11 Reference Limits (RLs) between ICNIRP and IEEE for Occupational Exposure



[23] This Hirata's slide and other Hirata's Figures were sent to the Author from the Pr. Akimasa Hirata, keynote-speaker to the EMC Europe 2020 plenary open-session 23 September 2020 'Human Exposure Standards and Compliance Assessment– 5G and Beyond'

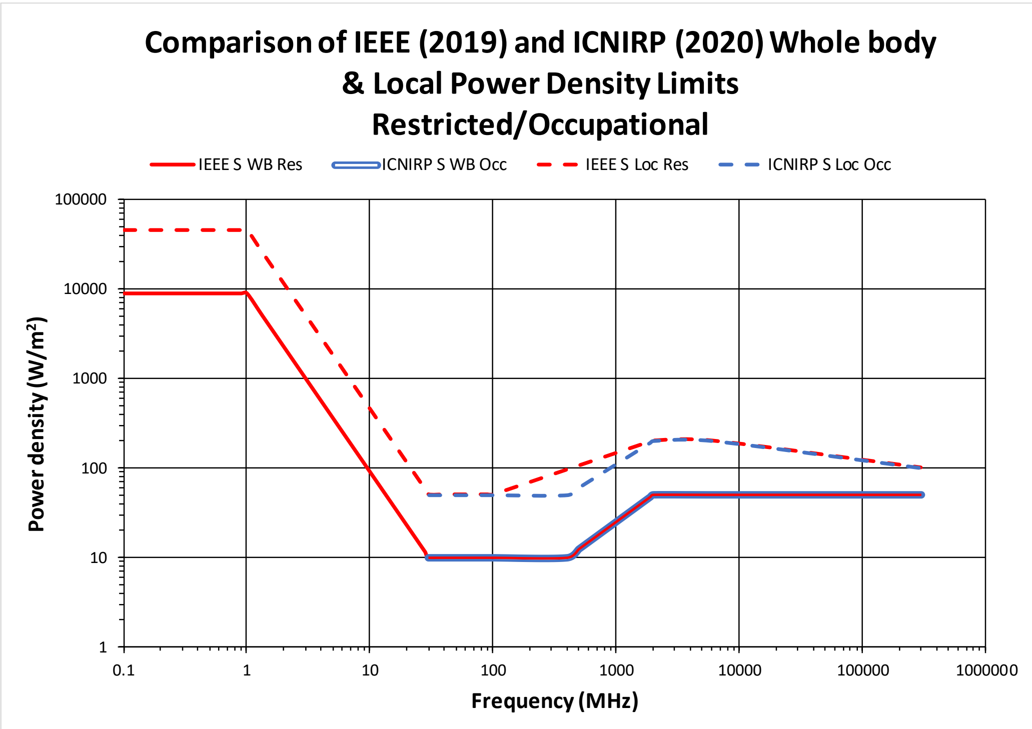
The following Figure (source, IEEE/ICES[24] Ric Tell, 4 June 2020) compares *IEEE C95.1 (2019)* and *ICNIRP (2020)* whole-body and local exposure-limits.

Figure 9.12 IEEE C95.1 (2019) versus ICNIRP (2020) whole-body and local exposure-limits



The following Figure (IEEE/ICES Ric Tell, 4 June 2020) compares IEEE C95.1 (2019) and ICNIRP (2020) whole-body and local power-density limits only for **restricted/occupational**.

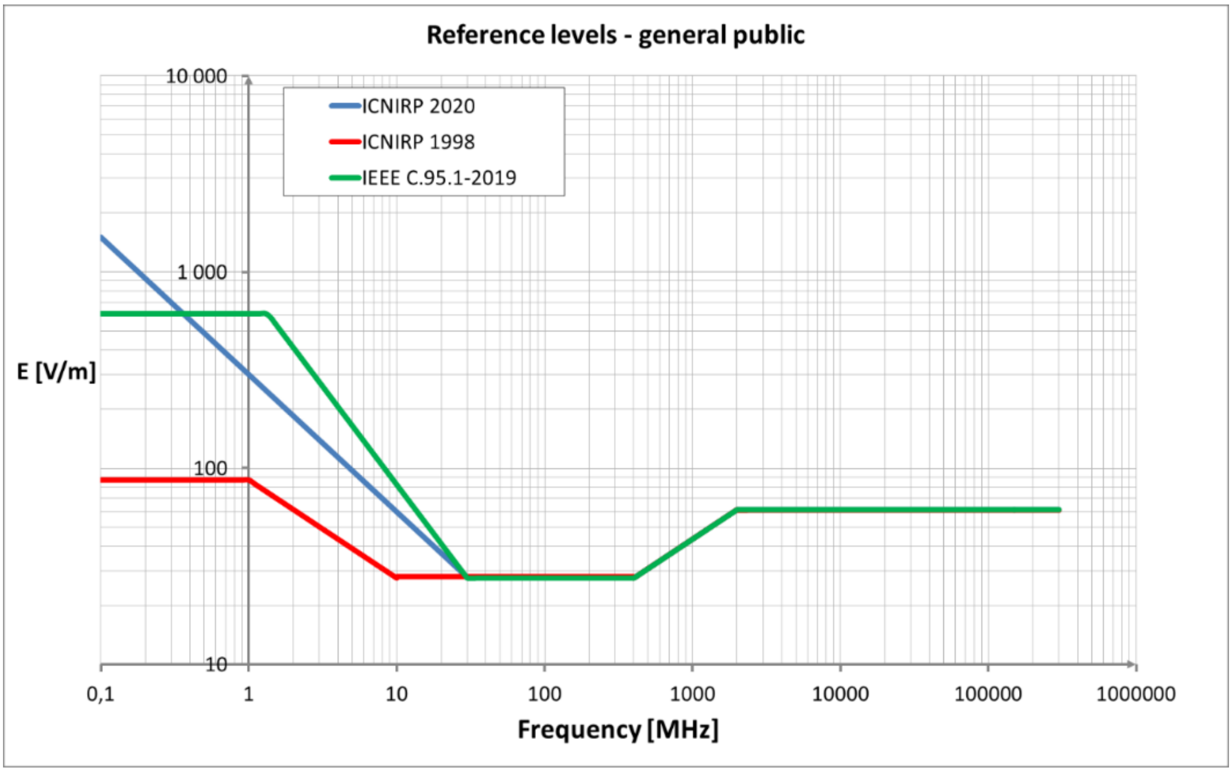
Figure 9.13: IEEE C95.1 (2019) versus ICNIRP (2020) whole-body and local exposure-limits



[24] ICES is the IEEE International Committee on Electromagnetic Safety

The following figure (source Dr Lewicki Fryderyk)[25]. Note that the ICNIRP (2020) electric field reference-levels for general-public stop at frequencies above 2 000 MHz. Electric-field units and measurements are convenient for Administrations, which monitor field-strengths. As between 100 kHz and 10 MHz, the more stringent value of ICNIRP (2010) or ICNIRP (2020) for every frequency should be followed, below 6.27 MHz the general public limit is 83 V/m.

Figure 9.14: Reference levels- general public for the ICNIRP (1998), IEEE (2019) and ICNIRP (2020) Guidelines



[25] Presentation at the ITU Regional Symposium for Europe and CIS on Spectrum Management and Broadcasting 02 July 2020, Electromagnetic Fields and 5G Implementation.

9.3.5 ICNIRP 1998, ICNIRP 2020 and IEEE 95.1 2019 limits applicable to cellular handsets

In this evolving era of data services, there is a marked difference in the way the user holds the handheld. In cellular conversation the person may hold the handset tightly against one ear such that it is in tight proximity to the brain. With data, one holds the mobile device in his hands or knees, which is a different hazards environment, probably more benign

Table 4 of ICNIRP (1998) stated localized SAR (*head and trunk*) from 10 MHz to 10 GHz, as well as localized SAR (*head and trunk*) from 100 kHz to 10 MHz is **2.0 (W kg^{-1})**, averaged over 10 g tissue. In this Document Table 9.4: ICNIRP (2020) Guidelines in brief; Basic Restrictions also specifies for *head and torso*, at 100 kHz−6 GHz, ΔT 2°C, spatial averaging 10 g, temporal averaging 6 min, health-effect level 20 W/kg, reduction-factor 2, workers 10 W/kg, reduction-factor 10, general-public **2 W/kg.** The ICNIRP (2020) local SAR restrictions (100 kHz to 6 GHz) are given in ICNIRP (2020) Table 2 'Basic restrictions for electromagnetic field exposure from 100 kHz to 300 GHz, for averaging intervals ≥6 min'; the values are unchanged compared to ICNIRP (1998): **2.0 (W kg^{-1})**.

ICNIRP (2020) introduces a new basic restriction (S_{ab}, absorbed power density) from 6 to 300 GHz of 20 W/m^2 for the public; see ICNIRP (2020) Tables 1 and 2. Additional reference levels for local exposure averaged over 6 minutes are given in ICNIRP (2020) Table 6. Whether the basic restriction or the reference level should be used for compliance is determined by Notes 5 and 6 of Table 6; see the underlined Notes of Table 9.3: (ICNIRP Table 6) Reference levels for local exposure, averaged over 6 minutes, to electromagnetic fields from 100 kHz to 300 GHz (unperturbed rms values) in this Document. These new basic restrictions/ reference levels are relevant for **International Mobile Telecommunications (IMT) 5G** devices operating at higher frequencies; see more details on 5G in paragraph 9.9.3.

The IEEE C95.1 (2005) p. 78 stated 'The peak spatial average SAR values have been changed from 1.6 W/kg and 8 W/kg for exposure of the public and exposures in controlled environments to 2 W/kg and 10 W/kg, respectively. Similar sentence 'The peak spatial-average SAR (psSAR) values were changed in IEEE Std C95.1-2005 from 1.6 W/kg and 8 W/kg for exposure of the public and exposures in controlled environments to 2 W/kg and 10 W/kg, respectively' appears in IEEE C95.1 (2019) p. 72. Therefore, the 1995 SAR level 1.6 W/kg was changed in 2005, and stays 2 W/kg in IEEE C95.1 (2019)[26].Table 9.5: C95.1-2019 (Table 5) – Dosimetric Reference Limits, DRLs (100 kHz to 6 GHz) in this Document specifies for Local exposure (head and torso) **2 W/kg** for persons in unrestricted environments.

[26] See IEEE (2019) Table 5—DRLs (100 kHz to 6 GHz)

9.4 Assessment of near-field and far-field exposures

9.4.1 *Near-field exposure levels, analysis and measurements: cellular handsets*

The general public receives the highest exposure from handheld devices such as mobile phones, which deposit most of the RF energy in the brain and surrounding tissues; typical environmental exposures to the brain from handsets are several orders of magnitude higher than those from mobile-phone base stations on rooftops or from terrestrial television and radio stations. As far as exposure levels are concerned, a distinction is made between the fixed radiating transmitters of the base stations and the portable handsets. The hazards from fixed transmitters refer to the field-strength and power-density generated, whereas handset hazards are considered mainly by the Specific Absorption Rate (SAR) value. The reason for the two different approaches is that the far-field[27] signal (easily simulated and measured) is practical to analyse EMF human exposure, radiated for the fixed wireless stations; whereas the handset, which is used in the proximity of the user's body; the body configuration in conjunction with the handset design have a strong impact on the EMF so called near-field[28]. The SAR, related to the temperature rise due to the EMF, defines the threshold levels for the handsets. In terms of exact definition, the SAR is 'the time derivative of the incremental energy (dW) absorbed by (dissipated in) an incremental mass (dm) contained in a volume element (dV) of a given mass density (ρ_m)' (see Recommendation ITU-T K.91); it is expressed in W/kg.

$$SAR = \frac{d}{dt}\left(\frac{dW}{dm}\right) = \frac{d}{dt}\left(\frac{dW}{\rho_m dV}\right) \qquad (9.1)$$

Table 9.9, see also IARC 2013 p. 116 Table 1.15, compares the absorption levels in ICNIRP 98[29], European Community (EC)[30] and North America[31] in uncontrolled environments; the following Table specifies the exposure limits for the partial body limit for mobile devices[32].

Table 9.9: Maximal power from handsets: Specific Absorption Rate (SAR) (W/kg)

ICNIRP 1998	European Community	USA and Canada
From 10 MHz to 10 GHz; localized SAR (head and trunk)		portable devices; general public / uncontrolled
2.0; averaged over 10 g tissue (it is also ANSI/IEEE C95.1-2006 level)		1.6; averaged over 1g tissue

[27] Recommendations ITU-T K.91 p.7 and K.61 p.2 define far-field 'That region of the field of an antenna where the angular field distribution is essentially independent of the distance from the antenna. In the far-field region, the field has predominantly plane-wave character, *i.e.*, locally uniform distribution of electric field-strength and magnetic field-strength in planes transverse to the direction of propagation'. More details in section 5.6.7 near-field to far-field.

[28] ITU-T K.91 p. 8 defines near-field 'The near-field region exists in the proximity to an antenna or other radiating structure in which the electric and magnetic fields do not have a substantially plane-wave character but vary considerably from point to point'. The reactive near-field of an antenna with maximum extension D is defined as Max(λ, D, $\frac{D^2}{4\lambda}$) where λ denotes the wavelength; to be compared to the *Fraunhofer* distance defining the far-field boundary of directive antennas as 2 D^2/λ.

[29] On 3 January 2021, European Community didn't change yet the reference to ICNIRP 1998. To remind, the limits for power density of ICNIRP 2020 and the IEEE Standard for whole-body exposure to continuous fields above 30 MHz are identical.

[30] References: ICNIRP 1998 p.509 Table 4; 1999/519/EC Annex III, Table 1 and IEC 62209-1 ed1.0; IEEE 1999 p. 29.

[31] FCC 1997 OET Bulletin 65 p. 75 (FCC 2012 CFR 47 FCC § 2.1093) and 1999 Canada Safety Code 6. NOI FCC 13-39 or R&O FCC 03-137 2013 keeps the SAR levels unchanged; see 8.3.4.4 Indicators of the USA.

[32] Moreover, for frequencies above 6 GHz currently used exposure limits of FCC and ICNIRP are not consistent, *i.e.*, there are inconsistencies between SAR and power-density basic restrictions at the transition frequency.

SAR can be ascertained[33] in three ways as indicated by the following equations:

$$\text{SAR} = \frac{\sigma e^2}{\rho} = C_i \frac{dT}{dt} = \frac{J^2}{\sigma\rho} \tag{9.2}$$

For pulsed or brief applications of RF energy, the exposure duration is not long enough for significant conductive or convective heat transfer to contribute to tissue temperature rise. In this case, the time rate of initial rise in temperature (slope of transient temperature response curve) is related to SAR through (see ICNIRP 2009 Vecchia pp. 52 and 60),

$$\text{SAR} = C_i \frac{\Delta T}{\Delta t} \tag{9.3}$$

where:

e : value of the internal electric field-strength in the body tissue (V/m)

σ : conductivity of body tissue (S/m) (Siemens per meter, or mho per meter)

ρ : mass density of body tissue (kg/m^3)

C_i : heat capacity of body tissue (J/kg ^{0}C)

dT/dt : time derivative of temperature in body tissue (^{0}C/s)

J : value of the induced current density in the body tissue (A/m^2).

ΔT : temperature increment (°C);

Δt : pulse width or duration of RF exposure (s).

Threshold levels for the maximal peak are set by manufacturers according to international standards and it is difficult for national regulators to deviate. The handset is working in full output power in the worst connection conditions (obstacles or long distance to base station) and in minimum output power in the best connection conditions (line of sight and close to the base station).

The maximum SAR level for different mobile phones varies according to technology; SAR is also influenced by technical parameters such as the antenna used and its placement within the device. The SAR information for a mobile phone is available from the mobile manufacturers' forum website http://www.sartick.com/.

9.4.2 *Simulations and tests of mobile phones*

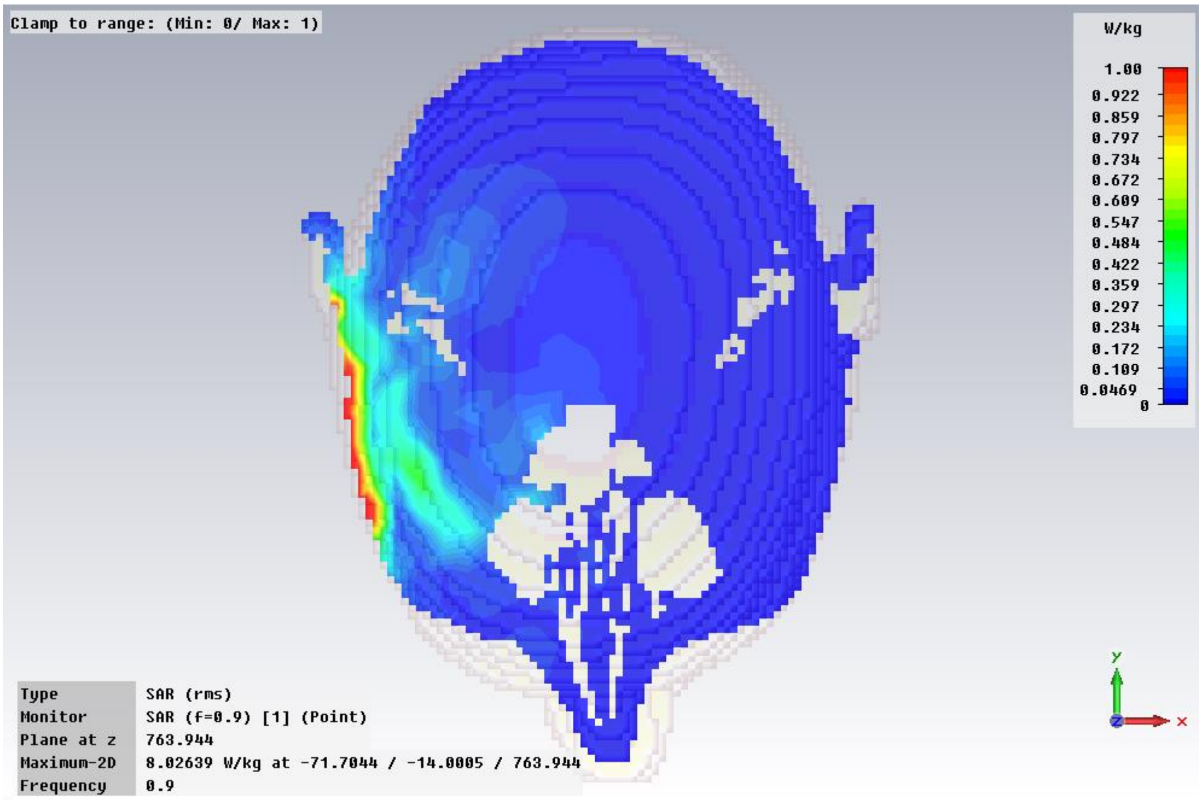
The near-field SAR measurements are complicated and require advanced instrumentation techniques to carry them out. SAR measurements are carried out according to the standardized protocols. Main international measurement standards for measuring the SAR in the human head are the International Electrotechnical Commission (IEC)[34] IEC 62209 and IEEE 1528 standards. SAR measurements are exclusive, relative to the power-density and field-strength measurements in the far-field. In view of the interaction between the EMF and the user body, SAR levels are measured by using a so-called 'phantom', which represents the human head (Kuster, Balzano and Lin 1997 p.21). IARC 2013 p. 58, fig. 1.12 specifies variation in SAR as a function of frequency in adult and child phantoms. Due to the closer proximity of the

[33] See Recommendation ITU-R BS.1698 p. 72 and Recommendations ITU-T K.52 p.4, K.61 pp. 2-3 and K.91 p. 12, IEEE Std 1528-2003 pp. 11-12 and ICNIRP 2009 Vecchia p. 47, ICNIRP 2020 App. A, equations 9-11.
[34] When ICNIRP was established, IEC was expected to develop human exposure guidelines; but there was a clear agreement between ICNIRP and IEC to share responsibility: ICNIRP focuses on exposure guidelines development and IEC on exposure assessment standards. See IEC standards in paragraph 9.9.4.

phone to the brain of children compared with adults, the average exposure from use of the same mobile phone is higher by a factor of 2 in a child's brain and higher by a factor of 10 in the bone marrow of the skull; see IARC 2013 p. 408.

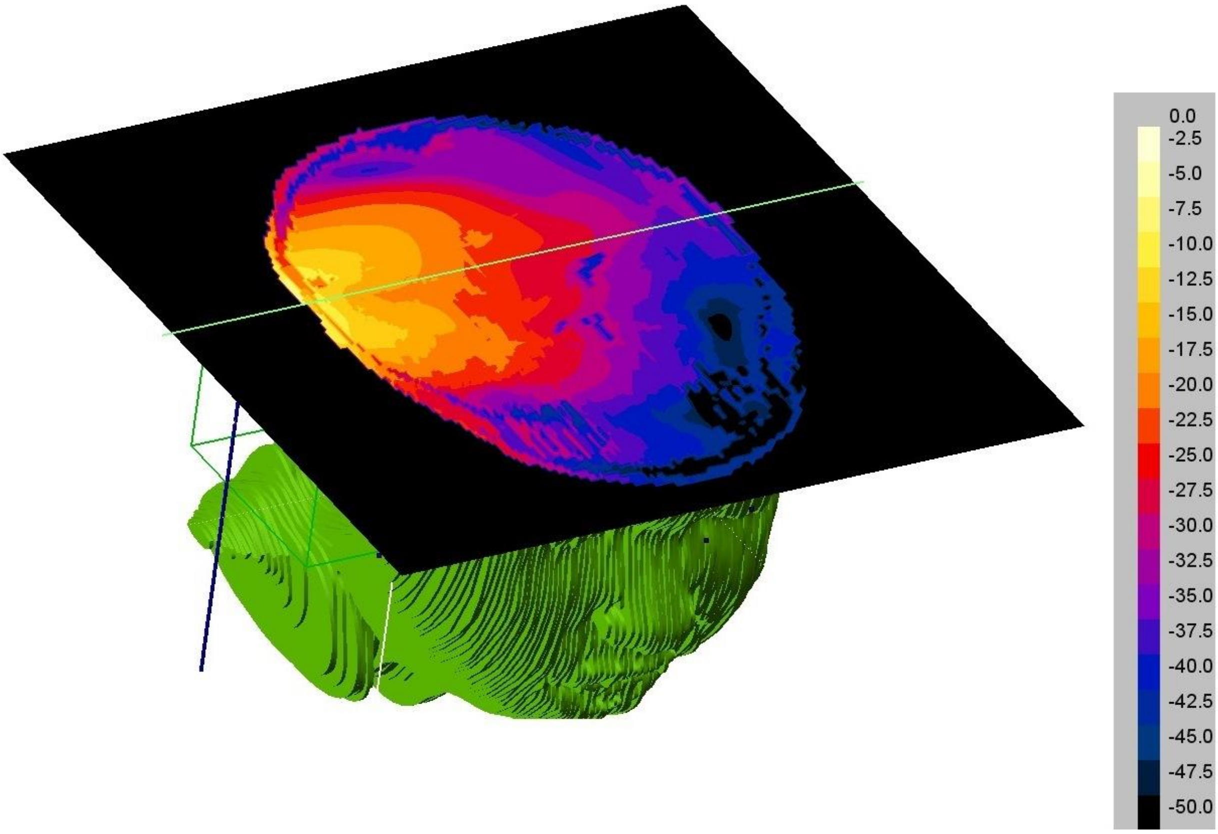
The mobile phones are tested for compliance at their highest possible power level through rigorous tests and multiple SAR measurements. Handsets rarely operate at maximum power levels during everyday use; therefore, SAR values reported for each model of mobile phone tend to overstate real-life exposure levels. Each model of mobile phone is tested using internationally agreed testing procedures as outlined in relevant standards. The handsets are tested using both a 'phantom' head and a separate 'phantom' torso for body-worn measurements. The phantoms are filled with liquids that simulate human tissue, such that the relevant electrical properties are similar to the human tissues. SAR values are measured with the phone at its different operating frequencies and in a range of positions. A probe inside the liquid measures the electric field-strength inside the phantom, and uses this to determine the maximum SAR value for the model of phone in each particular configuration. As a result, the testing is both complex and time consuming; for full compliance testing, the process can take up to several weeks depending on the model in question.
Figure 9.15 (source: Holon Institute of Technology) depicts SAR phantom simulations, 900 MHz, 0.5 Watt emission. Figure 9.15 shows the numerical SAR simulation of peak spatial SAR distribution in a magnetic resonance imaging (MRI) based human head phantom, normalized to 1W antenna input power. The location of the maximum SAR depends on the antenna structure, head anatomy and operating frequency. At Figure 9.15, the spatial peak (the area in red) occurs close to the surface at the ear where the handset is placed. The ICNIRP 1998 and 2020 EMF exposure limit for the head peak spatial average SAR is 2 W/kg, where the compliance measurements/calculations are compared to. The penetration of the RF EMF in the human head is rapidly slowed down due to the high attenuation of propagation of RF fields in the human tissues.

Figure 9.15 Numerical simulation of Specific Absorption Rate (SAR)



Based on MRI based head model, Figure 9.16 depicts another SAR simulation[35]. The spatial peak SAR distribution at 900 MHz for a three years child, generated by a half-wave dipole antenna, normalized to 1W antenna input power. The spatial peak SAR distribution is 0.096 W/kg. The other values are normalized and shown as dB below 0.096 W/kg; the scale is inserted in the graph. As mentioned, maximum average power levels of realistic devices are less than 0.2 W, and in realistic scenarios significantly lower than these values. It should be noted that the SAR averaging is performed as numerical post processing. Depending on the applicable limits, the 1g and 10g averaging SAR's are calculated in a cubical volume around the maximum spatial peak SAR, as defined in IEEE 1529[36].

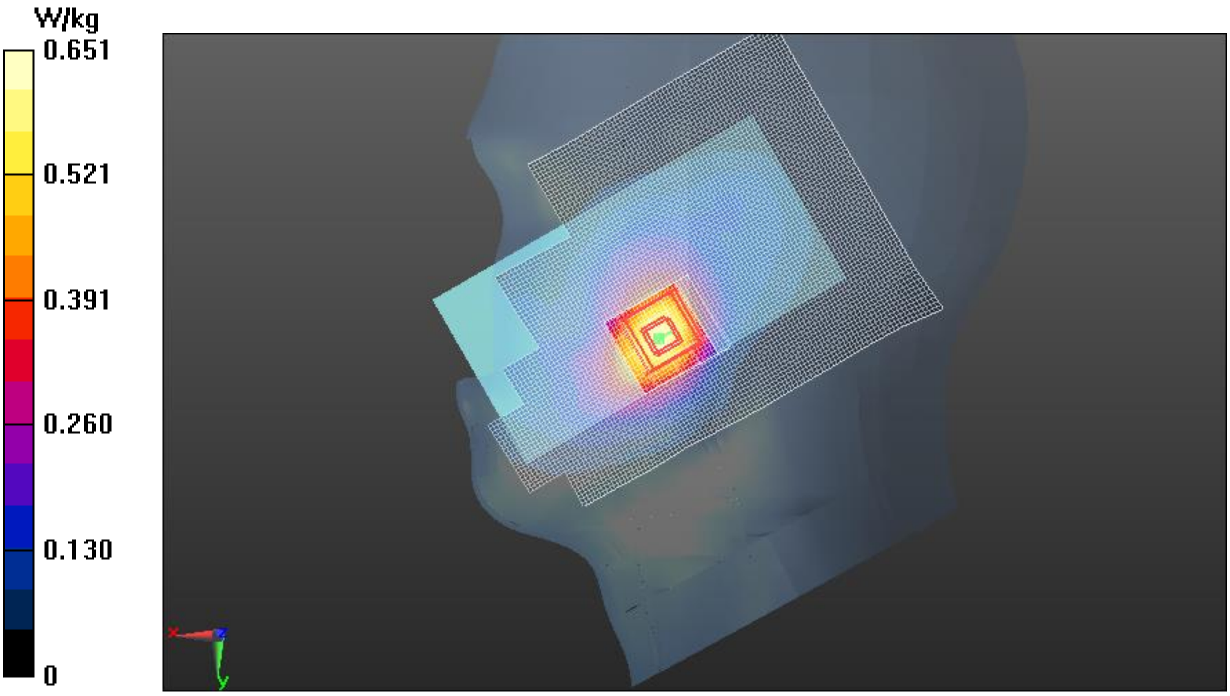
Figure 9.16 Numerical simulation of SAR; for a three years child



The following Figure is a plot of real measurements; typical SAR measurements result for a commercial mobile phone device; the results are lower than 2 and 1.6 W/kg.

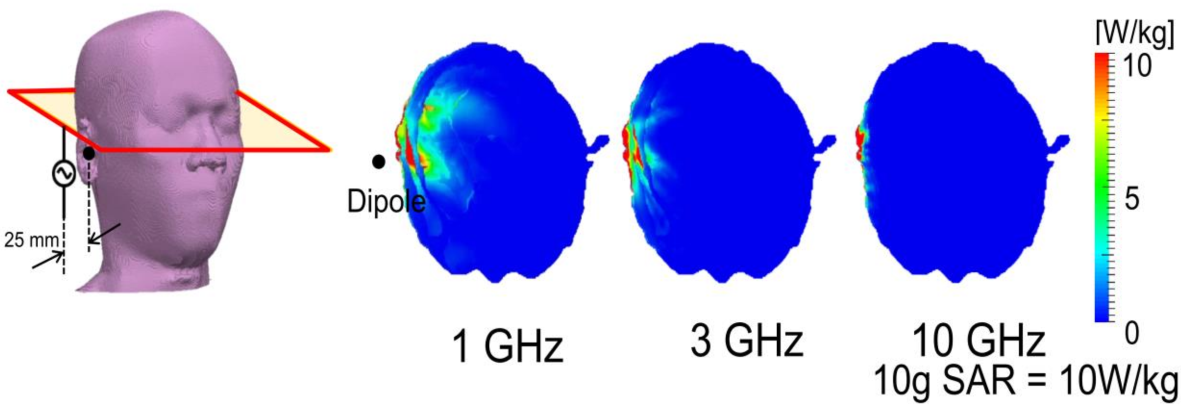
[35] The two Figures (Figure 9.16 and Figure 9.17) of SAR simulations and measurements were prepared by Dr. Jafar Keshvari- Chairman, IEEE International Committee on Electromagnetic Safety (ICES).
[36] Methods for the assessment of electric, magnetic and electromagnetic fields associated with human exposure

Figure 9.17 SAR real measurement for a commercial mobile phone



The following Hirata's Figure depicts measured SAR in biological tissues.

Figure 9.18 Measured power absorption in biological tissues



In 2013, the French ANFR measured the SAR of 77 cellular terminals (15% were 4G), see *Rapport annuel* 2013 p. 44. No measurement exceeded the ICNIRP 1998 threshold of 2 W/kg. Nearly 89% of monitored terminals' SAR were less than 1 W/kg (twice lower than the regulatory limit), and 100% were less than 1.5 W/kg; the average SAR value was 0.56 W/kg, and 1.377 W/kg the highest measured value.

9.4.3 *Exposure levels far-field: fixed radiating stations*

For fixed radiating stations, the following two Tables refer only to the exposure limits for general public, unperturbed and uncontrolled environment (unlike the workers/ controlled/ occupational case), as it is the most significant to the public. ICNIRP 1998 (p. 511 Table 6) and EC Directive 2004/40/EC refer to 'occupational exposure' (same term is ICNIRP 2020), CFR 47 FCC §1.1310 refers to occupational/controlled exposures and 1999/519/EC to the protection of 'workers' (EC). The general public limits of ICNIRP 1998[37] (p. 511, Table 7) and the European Community 1999/519/EC (Annex III, Table 2) are identical, since ICNIRP (1998) levels have been endorsed by the European Commission's Scientific Steering Committee. The following Table specifies the closely identical exposure limits of ICNIRP 1998, 1999/519/EC and ANSI/IEEE C95.1-2006[38] for radiations from (mainly) fixed stations above 10 MHz; see also Table 9.2.

Table 9.10: ICNIRP, EC and IEEE/ANSI reference levels for general public exposure above

Frequency range	Electric field-strength (V/m)	Equivalent plane wave power-density S_{eq}(W/m^2)
10–400 MHz	28	2
400-2000 MHz	$1.375f^{1/2}$	f/200
2-300 GHz	61	10

The following Table specifies the U.S. Federal Communications Commission FCC (CFR 47 FCC §1.1310)[39] and Japan[40] (Japan 2015 p. 5) above 30 MHz. Table 9.11 details the maximum permissible exposure (MPE) limits for radiating emitters in uncontrolled environment: general public exposure.

Table 9.11: USA and Japan general population/uncontrolled exposure

Frequency Range (MHz)	Electric-Field (E) (V/m)	Power-Density (S) (mW/cm^2)[41]
30-300	27.5	0.2
300-1,500	$1.585f^{(1/2)b}$	f/1,500
1,500-100,000	61.4*	1

[b] Only in Japan, V/m is detailed above 300 MHz.

[37] For ICNIRP 2020, see Table 9.2: (ICNIRP Table 5) Reference levels for exposure, averaged over 30 minutes and the whole body, to electromagnetic fields from 100 kHz to 300 GHz (unperturbed rms values) To repeat ICNIRP 2020 and IEEE 2019 Standard for whole-body exposure to continuous fields above 30 MHz are identical.
[38] ANSI/IEEE C95.1-2006 exposure values in p. 25 Table 9 are similar (not to FCC) to the ICNIRP 1998 level (f_{MHz}/200 W/m^2); at10-400 MHz the IEEE Electric Field (E) and FCC are 27.5 (V/m), compared to 28 (V/m) the ICNIRP 1998 . IEEE provides an additional equation above 100 GHz: [(90xf_{GHz} –7,000)]/200 W/m^2.
[39] Rerieved on 2 January 2021. The recent FCC § 1.1310 radiofrequency radiation exposure limits p. 97 keeps the MPE (and SAR) limits un-changed; see NOI FCC 13-39 or R&O FCC 03-137 2013; FCC has received comments but has not taken further action in this proceeding.
[40] The pamphlet reference of 2012 (now 2015: 27 on Heisei year; March 2015) was endorsed by email from Kenichiro Yoshida, electromagnetic environment division radio; department telecommunications bureau, ministry of internal affairs and communications, 1 October 2012. The upper limit in Japan is 300 GHz and not 100 GHz as in USA. See also the Dutch 2018 National Institute for Public Health and the Environment, RIVM 'Comparison of international policies on electromagnetic fields'
[41] FCC uses different units than ICNIRP for power-density: mW/cm^2 and not W/m^2; W/m^2 = 0.1 mW/cm^2

Health Canada is the federal department responsible for protecting the health and safety of Canadians. For its part, Innovation, Science and Economic Development Canada (ex Industry Canada) is responsible for radio-communication, and has adopted Health Canada's SC6 limits in its standards and regulations. Health Canada has set limits for human exposure, which are published in a document commonly known as Canada Safety Code 6 (SC6). On 13 March 2015 Health Canada revised the 2009 limits (that were identical to the USA), and published new reference levels: Canada Safety Code SC6 (2015)[42]. The new limits are based on the latest available scientific evidence, including improved modelling of the interaction of radiofrequency fields with the human body. The updated rigorous SC6 science-based limits include slightly more restrictive reference levels in some frequency ranges, to ensure larger safety margins to protect all population, including newborn infants and children[43].
The following Table compares the exposure limits in ICNIRP 1998 (and 2020) FCC §1.1310 and the Canada Safety Code SC6; The Table details the power-density S_{eq}(W/m^2) thresholds in uncontrolled environment at some relevant RF. The Table demonstrates that Canada is the most restrictive.

Table 9.12: ICNIRP 1998, FCC §1.1310 and Canada Safety Code SC6 (W/m^2)

Frequency	ICNIRP 1998 & 2020	FCC §1.1310	SC6
300 MHz	2	2	1.291
1,500 MHz	*f*/200=1500/200=7.5	10	0.02619x $f^{0.6834}$ =3.88
3,000 MHz	10 W/m^2		0.02619x $f^{0.6834}$ =6.23
6,000 MHz	10 W/m^2		

42 More information is found at Health Canada http://www.hc-sc.gc.ca/ahc-asc/media/ftr-ati/_2014/2014-023fs-eng.php.

43 Since the publication of SC63, Industry Canada has published various regulatory documents for site compliance and equipment certification: RSS-102: RF Exposure Compliance of Radiocommunication Apparatus (All Frequency Bands); BPR-1: Part I: General Rules - Broadcasting Procedures and Rules; GL-01: Guidelines for the Measurement of RF Fields at Frequencies From 3 KHz to 300 GHz; Towers in your community – Facts about towers.

9.4.4 *The international, regional and national thresholds; comparative study*[44]

Exposure limits in various countries, including Japan, are found at the WHO website: http://www.who.int/docstore/peh-emf/EMFStandards/who-0102/Worldmap5.htm. In addition to the ICNIRP 1998 and 2020 Guidelines, various institutions define the allowed limits permitted in specific regions, e.g.,:

- FCC still utilises[45] the IEEE Std C95.1-1999. This standard is also approved previously by the ANSI (1992, ANSI/IEEE C95.1);
- IEEE/ANSI standard ANSI/IEEE C95.1-2006 (nor IEEE C95.1-2019) is not approved by FCC; and
- The European Council adopted ICNIRP 1998 values, see 1999/519/EC Annexes II and III, Tables 1 and 2.

The national thresholds reveal the regulator's risk tolerability; see Mazar 2009 p.12. In the far-field, at 400-1,500 MHz (which includes cellular transmission bands), the maximum allowed power-density level of ICNIRP (1998 and 2020) and Europe for the general public exposure is f (MHz)/200 W/m^2 (ICNIRP 1998 Table 7 and ICNIRP 2020 Table 5). At the 300-1500 MHz range, the U.S. thresholds are f (MHz)/150 W/m^2, which is higher by 4/3 (200/150), compared to the ICNIRP thresholds. Europe in general[46] follows the ICNIRP 1998 (and 2020) levels, the non-mandatory EU Council Recommendation 1999/519/EC (and the base station general public harmonised standard BS EN 50385:2017).
In contrast to the thresholds of power-density from cellular base stations, it is important to observe that North American regulations are more risk averse than 1999/519/EC and ANSI/IEEE C95.1-2006 Std (p.79) in the allowed Specific Absorption Rate (SAR) from the cellular terminal. The ICNIRP 1998 threshold, adopted by EC (EC General Council Recommendation 1999/519) and IEEE Std ANSI/IEEE C95.1-2006 (p.79) is **2.0** W/kg, while the limit in the U.S. CFR 47 FCC § 2.1093 and Canada (Health Canada, Canada Safety Code SC6) is **1.6** W/kg[47] for the partial body; see Table 9.9 above. The North American perception seems more rational (at least compared to Switzerland and Italy, dividing ICNIRP 1998 power levels up to 100, and Poland fixing the threshold to only 7 V/m), as the RF radiation power absorbed from the handset is much stronger, being much nearer to the user's body, compared to the received signal from the base stations; see Mazar 2011.

There is also a difference in the threshold levels among European countries; such a distinction however does not exist in RF standards. Northern Europe is more tolerant than Southern Europe; whereas East Europe (such as Poland and Bulgaria) seems more restrictive than West Europe. Switzerland, Italy and Poland apply up to 0.01 ICNIRP 1998 reference level for power-density above 2 GHz, acting against proven adverse health effects. Additionally, Switzerland also implements precautionary emission limitations, so-called installation limit values (ILV), at places of sensitive use, such as apartment buildings, schools, hospitals, permanent workplaces and children's playgrounds. Poland reduces the level by 50 times for public exposure, Luxembourg by 20 times and China is 12.5 times stricter. The U.S. is the most tolerant in regulating uncertain risks in RF human-hazards from base stations. The U.S. follows the FCC §1.1310 limits for general population /uncontrolled exposure (1.33 ICNIRP level).

[44] See, Human Radio Frequency Exposure Limits: an update of reference levels in Europe, USA, Canada, China, Japan and Korea; Mazar, EMC Europe 2016 Wroclaw
[45] See FCC 1997 OET Bulletin 65 and FCC 2011 Code of Federal Regulations CFR 47§1.1310.
[46] Despite an EU Recommendation (see WHO 2007 p.129), some EU countries adopt more restrictive thresholds; see WHO '*EMF world wide standards*.
[47] Even the averaging is more stringent in the U.S., as the limit is averaged over one gram; see FCC, OET Bulletin 65 p. 40 and OET Bulletin 65 Supplement C p.75, and not 10 grams as in ICNIRP 1998 p. 509 Table 4, EC 1999/519/EC and ANSI/IEEE C95.1-2006.

9.5 Calculating RF hazards from fixed transmitters

9.5.1 *Power-density, field-strength and safety-distances around fixed transmitters*

9.5.1.1 Free space calculations, one transmitter

Enclosed are some useful equations needed at this chapter.

$$s = \frac{p_t g_t}{4\pi d^2} = \frac{eirp}{4\pi d^2} \tag{9.4}$$

$$d = \sqrt{\frac{eirp}{4\pi s}} \tag{9.5}$$

$$e = \frac{\sqrt{30\, eirp}}{d} \tag{9.6}$$

$$d = \frac{\sqrt{30\, eirp}}{e} \tag{9.7}$$

$$|\vec{s}| = \frac{e^2}{z_o} = \frac{e^2}{120\pi} \tag{9.8}$$

where:

- p_t: transmitter power (watts)
- g_t: transmitter antenna gain (numeric)
- *eirp*[48]: equivalent isotropically radiated power (watts)
- s: power-density (watts/m^2) (serves as exposure limit)
- d: distance (m)
- e: electric field-strength (V/m) (serves as exposure limit)
- z_0[49]: characteristic impedance of free-space, 120π (Ohms) ≈ 377 (Ohms)

[48] ‘product of the power supplied to the antenna and the antenna gain in a given direction relative to an isotropic antenna’ ITU Radio Regulations, volume 1 provision 1.161. *eirp* is not necessarily the product of maximum power and maximum gain; it is the power radiated toward the point of investigation. The cellular transmitters are power controlled and they do not transmit all time at maximal level. Near a cellular antenna, below it, the eirp is low, as a sidelobe in elevation is much attenuated relatively to the antenna main-beam.

[49] z_0 relates the magnitudes of electric *e* and magnetic *h* fields; $z_o \equiv \frac{|\vec{e}|}{|\vec{h}|}$

9.5.1.2 Assessment, mainly far-field safety-distance

Equation (9.4) above calculates the power-density and equation (9.6) the field-strength at distance *d* from the emitter; both equations indicate that the distance from the radiated source is more significant than the source power level, as the power-density is linear with $eirp$ and $1/d^2$ with distance. Equation (9.5) calculates the safety-distance *d* from the emitter, given the power-density threshold s; equation (9.7) calculates distance *d* given the field-strength limit e. The safety-distance determines a contour around a specific antenna or mast; this profile determines the public uncontrolled/unperturbed environment at the far-field. According to equation (9.8) power-density s and electric field-strength e (in free-space conditions) are interchangeable (as parameter, not as specific magnitude) and can be replaced; therefore, the RF exposure (limit and measurements) is determined by power-density **or** the field-strength.

Interesting to note that due to far/near fields substances, the electric-field reference-levels of ICNIRP (2020) stop at frequencies above 2 000 MHz[50]. ICNIRP 2020 indicates that in terms of EMFs in the far-field[51] zone, the following rules apply: 'For EMF frequencies from >30 MHz to 2 GHz, ICNIRP requires compliance to be demonstrated for only one of the E-field, H-field or S_{inc} quantities in order to be compliant with that particular reference level. Further, S_{eq} can be substituted for S_{inc}'. 'For EMF frequencies from >30 MHz to 2 GHz, personal exposure within either the radiative or reactive near-field zones is treated as compliant if both the E-field and H-field strengths are below the reference level values described in the tables.' Considering the exposure is in the far-field, ICNIRP 2020 levels above 2 GHz refer only to power density.

The power-density and the Poynting vector are the vector-product of two vectors: the electric field-strength e and magnetic field-strength h. The power-density and the two field-strength vectors have a magnitude and direction of the flow of energy, while the transmitted power and safety-distance are just a scalar number. So, power levels from different emitters at the same RF are summed as scalar quantities. In practice, the weighted (see later) power-densities are added (as a scalar sum, not vector sum) at the point of investigation; it is explained as the human-hazards thresholds are derived from the scalar quantity energy (heat).

Normally, regulators adopt the worst-case value; *i.e.*, the maximum safety-distance is calculated, assuming:

- maximum antenna gain: point of investigation (POI) at the main antenna beam in azimuth, and sometimes also in elevation[52] (near the antenna, the elevation pattern is much attenuated);
- free-space propagation is usually assumed between the emitter and POI; even though there might be obstacles between the antenna and POI;
- maximum power of the transmitter: cellular base stations coverage to the edge of the cell and at maximum traffic loading; *i.e.*, all channels transmitting at their respective maximum power setting (see Recommendation ITU-T K.70); and
- weighted power-densities at different RF are summed in scalar quantity, even though power-density is a vector and their sums are not necessarily in-phase.

---

[50] Note that IEEE C95.1-2019 Tables do not provide the electric and magnetic field-strengths above 400 not 2000 MHz.

[51] ICNIRP 2020 indicates in p. 30 'As a rough guide, distances > $2D^2/\lambda$ (m), between $\lambda/(2\pi)$ and $2D^2/\lambda$ (m), and < $\lambda/(2\pi)$ (m) from an antenna correspond approximately to the far-field, radiative near-field and reactive near-field, respectively, where D and λ refer to the longest dimension of the antenna and wavelength, respectively, in meters.

[52] The antenna downtilt (up to 10^0) toward mobile telephone or broadcasting receivers affects the RF exposure because the antenna transmitting gain changes.

9.5.2 *Emissions transmitted from the same site: multiple-antenna installation*

The exposure criteria referred to thermal effect circumstances are frequency depended; see the following Table and Figure. For emissions transmitted from one location the cumulative safety-distance and field-strength are calculated, given:

$eirp_i$:	for each emitter (watts)	
$eirp_{eq}$:	equivalent cumulative *eirp*	(watts)
d_i:	safety-distance from each emitter	(m)
d_{eq}:	equivalent cumulative safety-distance	(m)
s_i :	power-density from each emitter	(W/m²) index i
s_{li} :	power-density **l**imit from each emitter	(W/m²) index i
e_i :	electric field-strength from each emitter	(V/m) index i
e_{li} :	electric field-strength **l**imit from each emitter	(V/m) index i

9.5.2.1 General case: Simultaneous exposure to multiple sources at different frequency ranges

As already explained, ICNIRP 1998 power-density and field-strength reference levels (s_l and e_l) are RF dependent. In the case of emitters with different thresholds, we may define (not mentioned in ICNIRP 1998 nor ICNIRP 2020) the equivalent cumulative safety-distance d_{eq}, which equals the square root of sum of individual square safety-distances $d_{eq} = \sqrt{\sum_i d_i^2}$.

From equation (9.5) above, each individual safety-distance equals $d_i = \sqrt{\frac{eirp_i}{4\pi s_{li}}}$.

The $eirp_i$ of each emitter is weighted by the inverse of its power-density limit s_{li}, thus the square-root of the weighted sum[53] provides the equivalent cumulative safety-distance, *i.e.*,:

$$d_{eq} = \sqrt{\sum_i d_i^2} = \sqrt{\sum_i \frac{eirp_i}{4\pi s_{li}}} = \sqrt{\frac{eirp_1}{4\pi s_{l1}} + \frac{eirp_2}{4\pi s_{l2}} + ... + \frac{eirp_n}{4\pi s_{ln}}} \quad (9.9)$$

For each point of investigation (POI), it is needed to check the compliance for the power-density s_i (or its electric component e_i) at each frequency band, relative to the threshold s_l (or e_l). Based on the total cumulative weighted power-density s_t (see ITU-R Monitoring handbook 2011 p.517 and ITU-T K.83 p. 11), the total exposure quotient (or cumulative exposure ratio) should be less than 1:

$$s_t = \sum_{i=1}^{n} \frac{s_i}{s_{li}} = \frac{s_1}{s_{l1}} + \frac{s_2}{s_{l2}} + ... + \frac{s_n}{s_{ln}} \le 1 \quad (9.10)$$

The requirement for the total 'cumulative weighted field-strength exposure ration' w_t (see recommendations ITU-T K.91 , K.70 and K.52) is[54]:

$$s_t = w_t = \sum_i \left(\frac{e_i}{e_{li}}\right)^2 \le 1 \quad (9.11)$$

Given that at a particular frequency *i*, $eirp_i$ is the temporal averaged *eirp*, and $eirp_{th,i}$ is the *eirp* threshold relevant to the particular antenna parameters and accessibility conditions- a site is

53 Sum of squares, where each $(d_i^2) = \frac{eirp_i}{4\pi s_{li}}$

54 Even calculated differently, s_t and w_t are identical.

compliant if the sum of the normalized $eirp_i$ of each RF is smaller than 1. The following equation (9.12) is the compliance criterion (see K.52):

$$\sum_i \frac{eirp_i}{eirp_{th,i}} \leq 1 \tag{9.12}$$

Calculations done separately for each frequency range allow evaluating the cumulative exposure ratio.

9.5.2.2 *Emissions at the same frequency*

For the particular case of emitters transmitting at the same RF, or at a frequency range[55] whose limits are frequency independent (like 10–400 MHz and 2–300 GHz), the power-density limits are equal for all transmitters, emitting at the same frequency range, *i.e.*, in equation (9.9) $s_{l1}= s_{l2}=\ldots =s_l$. Therefore,

$$d_{eq} = \sqrt{\sum_i d_i^{\,2}} = \sqrt{\sum_i \frac{eirp_i}{4\pi s_{li}}} = \frac{1}{4\pi s_l}\sqrt{eirp_1 + eirp_2 + \ldots + eirp_n} \tag{9.13}$$

The equivalent cumulative $eirp$ is defined as the scalar sum of all the emitters' $eirp$; this equivalent $eirp_{eq} = \sum eirp_i$ is inserted in equation (9.13) to calculate the safety-distance[56].

$$d_{eq} = \sqrt{\frac{eirp_{eq}}{4\pi s_l}} = \sqrt{\frac{\sum eirp_i}{4\pi s_l}} \tag{9.14}$$

The requirement for the total field-strength and power-density exposure rations[57] w_t (see ITU-T K.91) and s_t are:

$$w_t = \sum_i \left(\frac{e_i}{e_l}\right)^2 = \frac{\sum_i (e_i)^2}{(e_l)^2} \leq 1 \tag{9.15}$$

$$w_t = s_t = \sum_i \frac{s_i}{s_l} = \frac{\sum_i s_i}{s_l} \leq 1 \tag{9.16}$$

[55] The 'frequency range' is the column's title 'frequency range' in ICNIRP 1998 reference Tables 6 and 7 and ICNIRP 2020 Table 5.

[56] For a scenario with antennas installed at one tower, in different levels, the equivalent cumulative safety-distance (and field-strength exposure) is calculated relative to an equivalent weighted altitude at the mast.

[57] Calculated differently, but identical solution is derived by equations (9.15) and (9.16); see footnote 54. Therefore, the field-strength ration in Figure 9.20 is also the power-density ration.

9.6 Simulations and measurements of RF exposure

9.6.1 *Calculated safety-distances, worst-case, multiple-antenna installation*

For a co-located antenna site of FM audio and TV broadcasting, point-to-point and cellular emitters, the cumulative far-field free-space horizontal safety-distance toward a point of investigation is calculated. The following Table is an Excel output calculating the safety-distances and field-strength from these typical emitters. The worst-case is computed, including the cumulative horizontal safety-distance and field-strength. Derived from the excel file, the following Table calculates radiations from a co-located site; cellular emitters, point-to-point and broadcasting. The two ratios (see last rows) indicate:

- specific field-strength at 50m and
- cumulative field-strength

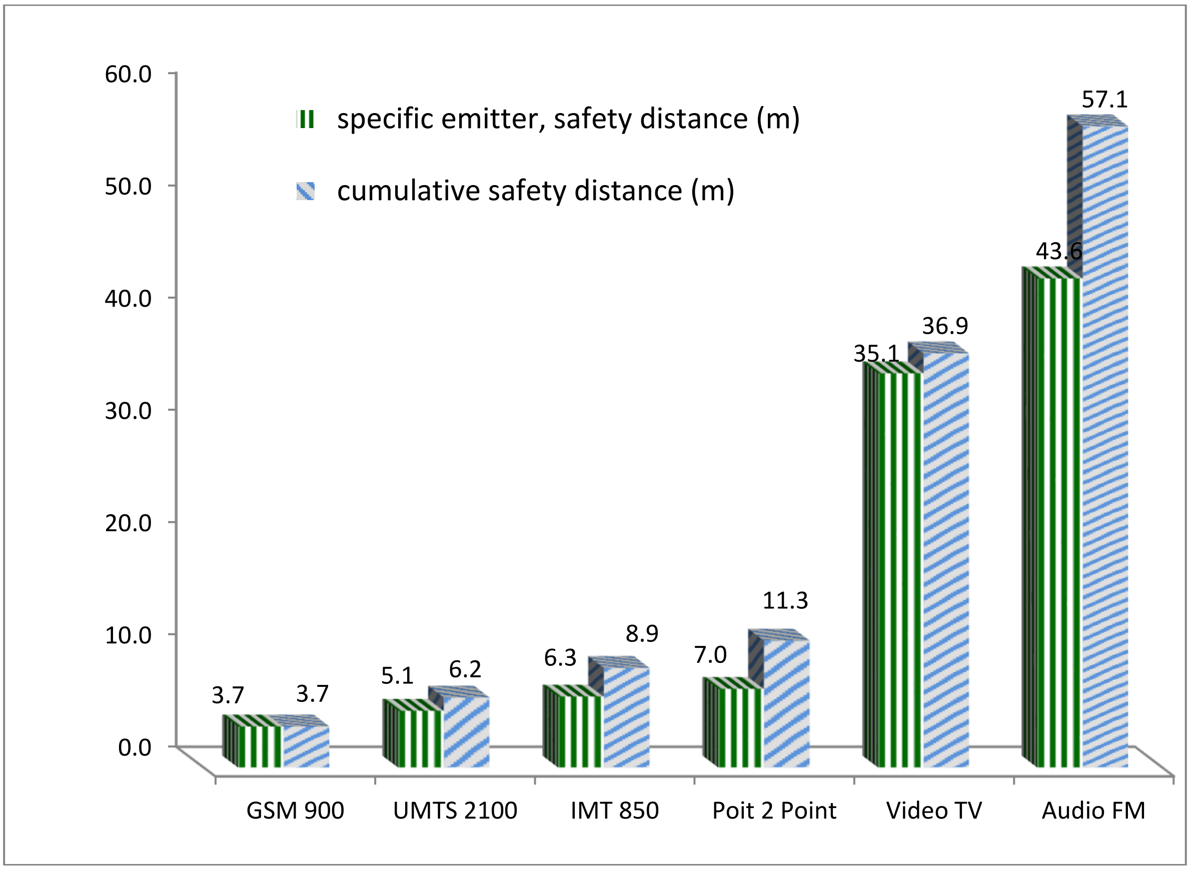
divided by ICNIRP 1998 (and 2020) level.

Table 9.13: Radiations from a co-located site: ratios to ICNIRP levels

Transmission System	**GSM 900**	**UMTS 2100**	**IMT 850**	**point-to-point**	**Video TV**	**AudioFM**
Frequency (MHz)	891	2,100	800	514		100
ICNIRP 1998 & 2020, power-density (W/m^2)	4.75	10.00	4.00	2.57		2.00
Antenna gain (dBi)	16	18		23	17	10
Antenna elevation: **real** pattern or model	742 265	TBXLHA	80010302_0824	ITU-R F.1336	ITU-R F.699	
Antenna altitude above ground level (m)	32	45	15	25	60	
Cable loss (dB)	1					
Power (Watt)	25	64	40	10	1,000	6,000
eirp (Watt)	800	3,210	2,000	1,580	39,810	47,660
Specific safety-distance (m)	**3.7**	**5.1**	**6.3**	**7.0**	**35.1**	**43.6**
Cumulative safety-distance (m)	**3.7**	**6.3**	**8.9**	**11.3**	**36.9**	**57.1**
ICNIRP 1998 & 2020, field-strength (V/m)	41.30	61.00	38.89	31.17		28.00
Specific field strength at 50 m (V/m)	3.10	6.21	4.90	4.35	21.86	23.91
Specific field-strength at 50m, ICNIRP 1998 & 2020, ration	**0.08**	**0.10**	**0.13**	**0.14**	**0.70**	**0.85**
Cumulative field-strength ration	**0.08**	**0.13**	**0.18**	**0.23**	**0.74**	**1.13**

Based on the transmitters' data of the co-located site in Table 9.13, the following four Figures depict worst-case calculations[58]. The safety-distances are horizontal relative to the mast.

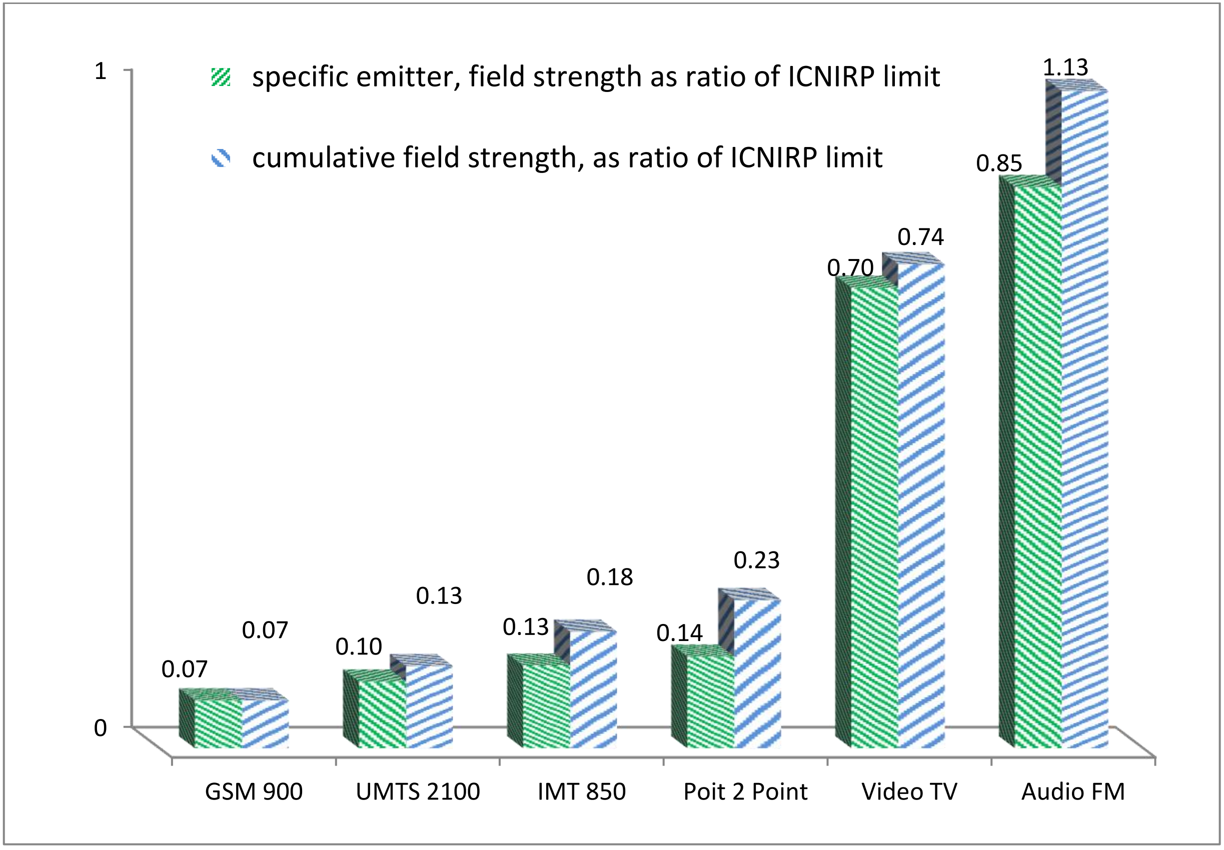
Figure 9.19 Cumulative horizontal safety-distance, co-located site; y axis (m)



Derived from Table 9.13, the following Figure depicts the cumulative field-strength exposure ratio, for point of investigation at 50 meters.

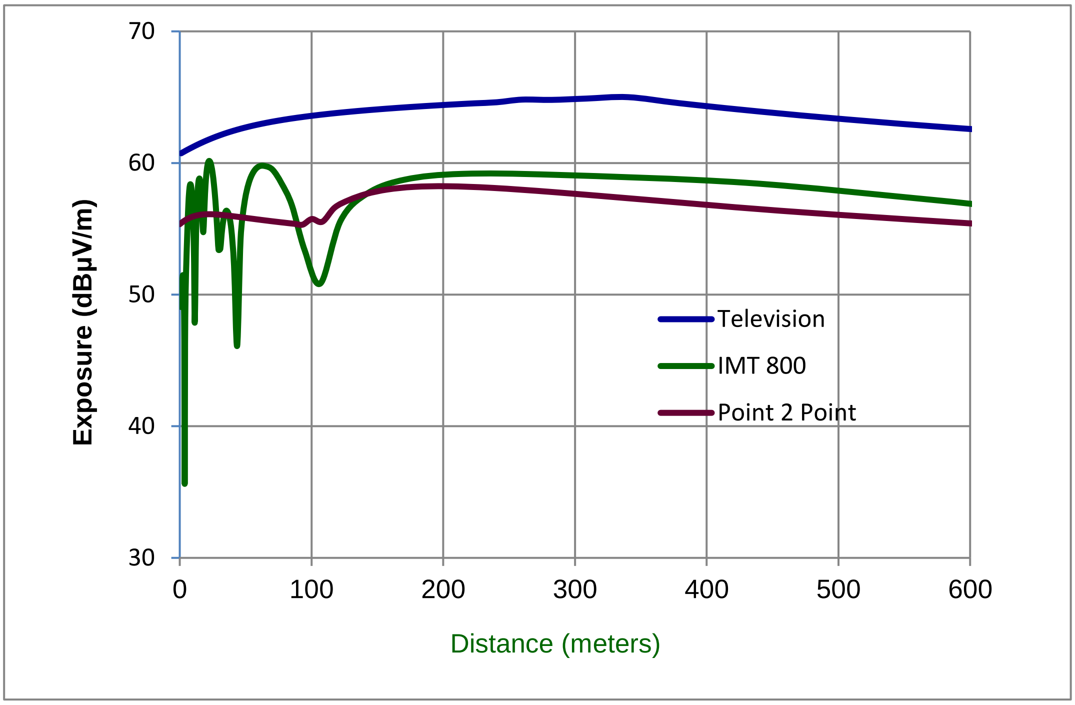
[58] Assuming **free-space** propagation, maximum antenna gain in **elevation** and azimuth, **maximum** transmitters' **power** (as an example the UMTS base stations use power control and may transmit up to 12 dB below their maximal power), **scalar** (and not vector) **summation** of power-densities.

Figure 9.20 Cumulative field-strength exposure ratio, for point of investigation at 50 meter



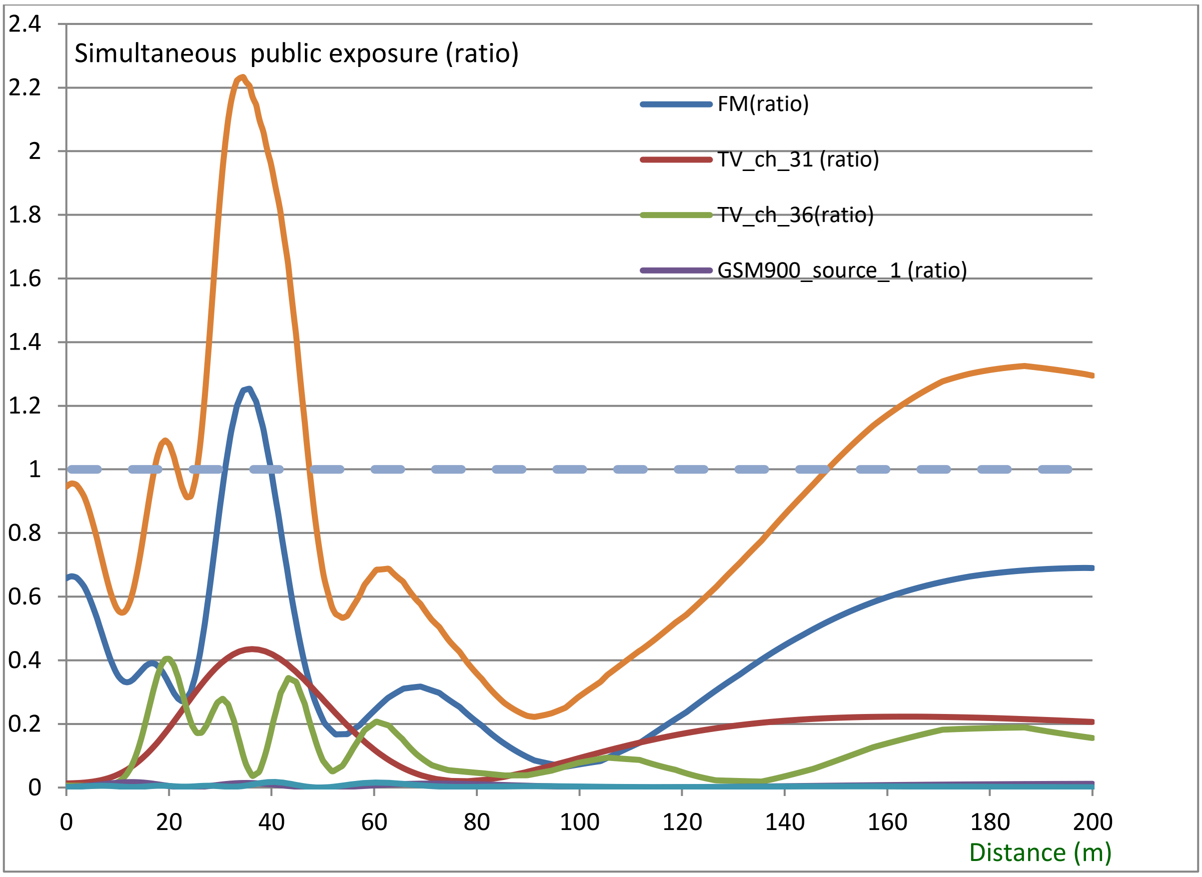
The field-strength in the following Figure of each transmitter is depicted in dBμV/m (dBu). The point-to-point and television antennas' elevation patterns are based on Recommendations of ITU-R F.1336 and F.699, respectively; the simulations provide conservative values, comparing the calculated patterns to real antenna, such as the IMT 850 (80010302_0824) elevation antenna pattern. The maximal exposure is not down the antenna mast, at the closest point near the station, due to the sidelobe attenuation in elevation, with and without down-tilt.

Figure 9.21 Field-strength (dBµV/m) vs. distance (m) of TV, IMT 850 and point-to-point



The following Figure depicts the separate and the cumulative exposure ratio W_t of different emitters at a co-located site[59].

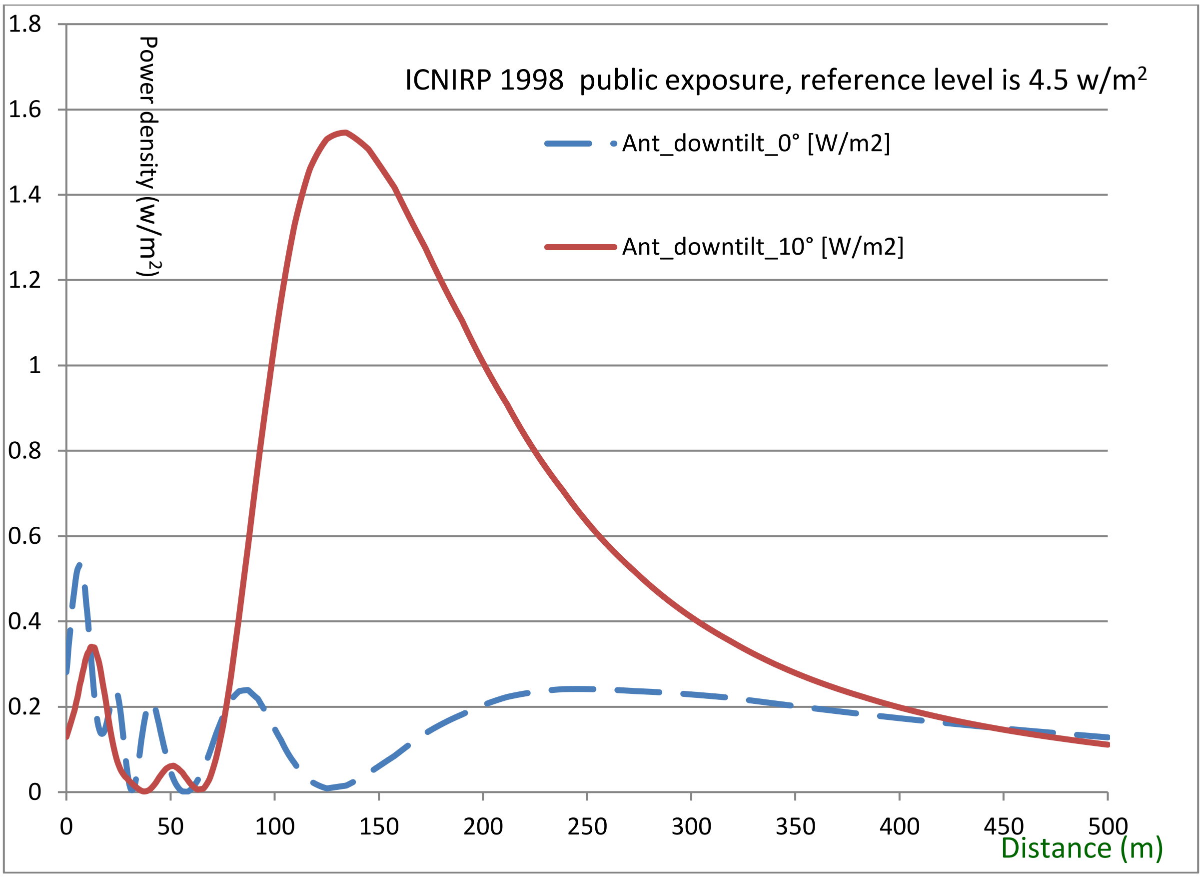
Figure 9.22 Coefficient W_t versus distance for a transmitting site with FM, TV and GSM



[59] See more details at Recommendation ITU-T 2020 K.70 Fig. I.5

The following Figure is derived from EMF-Estimator[60]. Depicted two cases: without downtilt, and with 10° downtilt, to show the power-density distribution derived from a typical GSM 900 transmitter.

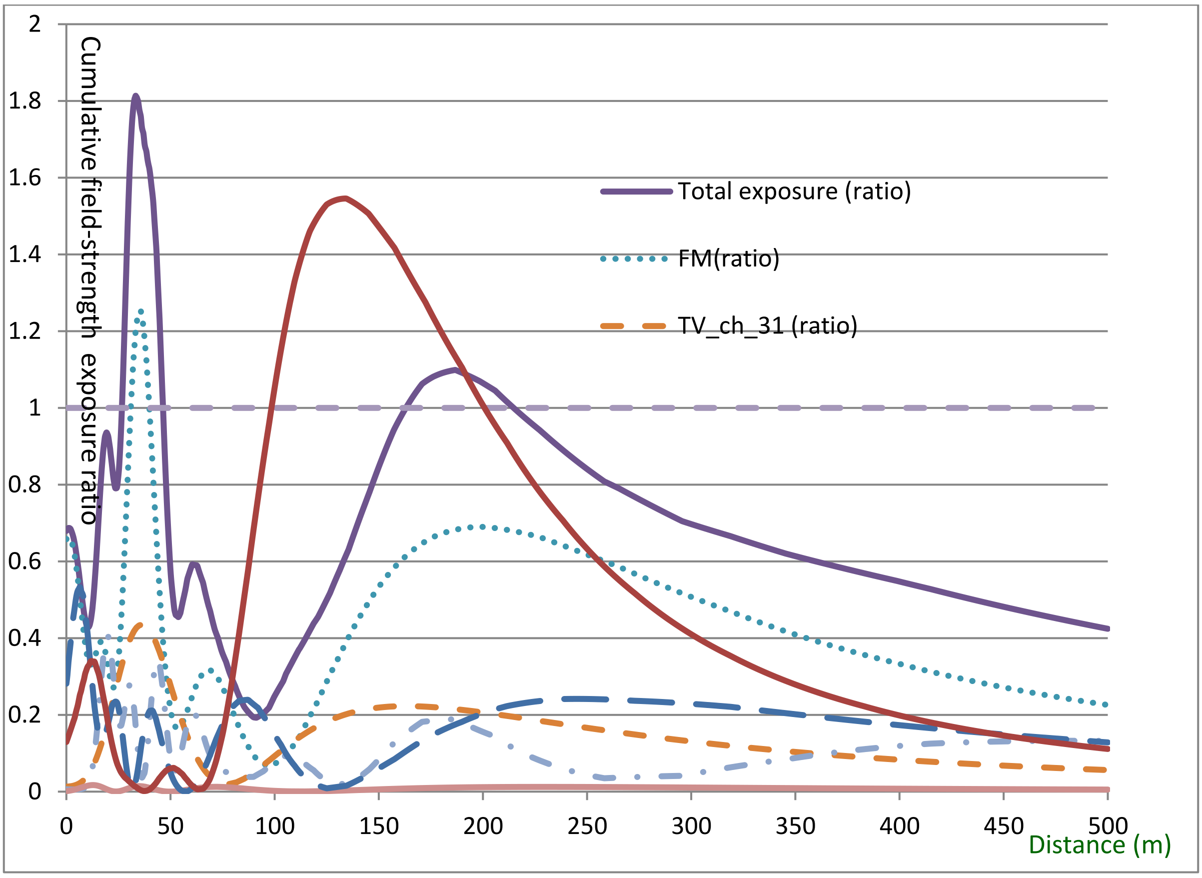
Figure 9.23 Power-density versus horizontal distance at near-field and far-field



[60] See more details in Recommendation ITU-T 2020 K.70 Fig. D.2

The following Figure[61] depicts the coefficient W_t distribution as a function of distance for a transmitting site with multi frequency range emitters: FM, TV and GSM 900 systems.

Figure 9.24 Field-strength coefficient W_t versus distance for a transmitting co-located site



[61] See also ITU-T 2020 K.70 Fig. 8-1

9.6.2 *Monitoring human exposure*

9.6.2.1 Recommendations, reports and standards on monitoring of human exposure

Monitoring of the human exposure is essential and serves as 'eyes and ears' of the regulator. The ITU-R *Spectrum Monitoring, Edition of 2011* sub-chapter 5.6 pp. 516-31 specifies non-ionizing radiation measurements. Additional significant information on characteristics of EMF measurements (procedures, techniques and instruments), comparison between predictions and measurements, examples of calculated field-strengths, limits and levels can be found in Recommendations ITU-R BS.1698, ITU-T K.52, K.61, K.70 and K.91. A software EMF-Estimator is attached to K.70[62] in order to support its application. The software calculates the cumulative exposure for the reference levels[63]. In addition to real measurements, a continuous software-monitoring of the antennas is significant for effective monitoring and enforcement. Such a program[64] collects information directly from the radio switch networks of the cellular carriers nationwide, in order to complete the cellular radiation measurements.
The June 2019 ITU-R Report SM.2452 'Electromagnetic field measurements to assess human exposure' provides significant measurements' information.
IEC standard IEC 62233 /EN 62233 specifies similar measurement methods for magnetic and electric fields of domestic appliances with regards to human exposure. The differences between the two standards are in the exposure limit values, which are specified as 'basic limit values and reference values' in Annex B of each standard. EN 62233 only allows the values specified in ICNIRP 1998 (ANSI/IEEE C95.1-2006, and ICNIRP 2020); in contrast, IEC 62233 provides two sets of exposure limits, and IEEE Std. C95.7-2014 recommends practice for RF safety programs; additional IEC standards on EMF human exposure are 2019 IEC 62311 and IEC 62369.

9.6.2.2 Monitoring of human hazards around the world

National websites such as France ANFR *mon cartoradio* and Italy *monitoraggio campi elettromagnetici* illustrate measurements. In response to public concern in India regarding the possible health effects of EMF exposure, the Indian Department of Telecommunications launched a web portal "Tarang Sanchar" with the aim of increasing public confidence and conviction regarding the safety and harmlessness of mobile masts, dispelling myths and misunderstanding.
Monitoring around the world reveals that repeatedly the power-density at common points is less than 1 per cent of ICNIRP 1998 (and ICNIRP 2020) threshold, and equivalently less than 10 per cent of the ICNIRP field-strength[65]; exposure levels due to cellular base stations are generally around one-ten-thousandth of the guideline levels (ICNIRP 2009 Statement p. 258). Moreover, irrespective of country, the year and cellular technology, exposures to radio signals at ground level were only a small fraction of the relevant human exposure standards. See the two comparative international RF exposure surveys of mobile communication radio base stations: 23 countries across five continents Rowley and Joyner 2012, and 260,000

[62] Amendment 2 adds Appendix I with distinct 32-bit and 64 bit versions of the 2020 EMF estimator software
[63] The Rapporteur for ITU-T Question 3/5 Dr. Lewicki Fryderyk – Hurt prepared the last four

Figure 9.21 to Figure 9.24, using EMF-Estimator
[64] The program implemented since 2010 by the Noise and Radiation Department at the Israeli Ministry of Environmental Protection enabling the Radiation Commissioner to monitor more than 30,000 UMTS sectors of base stations around the country, and receive all radiation related data from every antenna, 24 hours a day, 365 days a year.
[65] As already stated power-density and electric field-strength in the far-field are interchangeable (but they are not identical); see WHO 2007 p. 30, ANFR 2007 and Viel et al. 2009 use V/m.

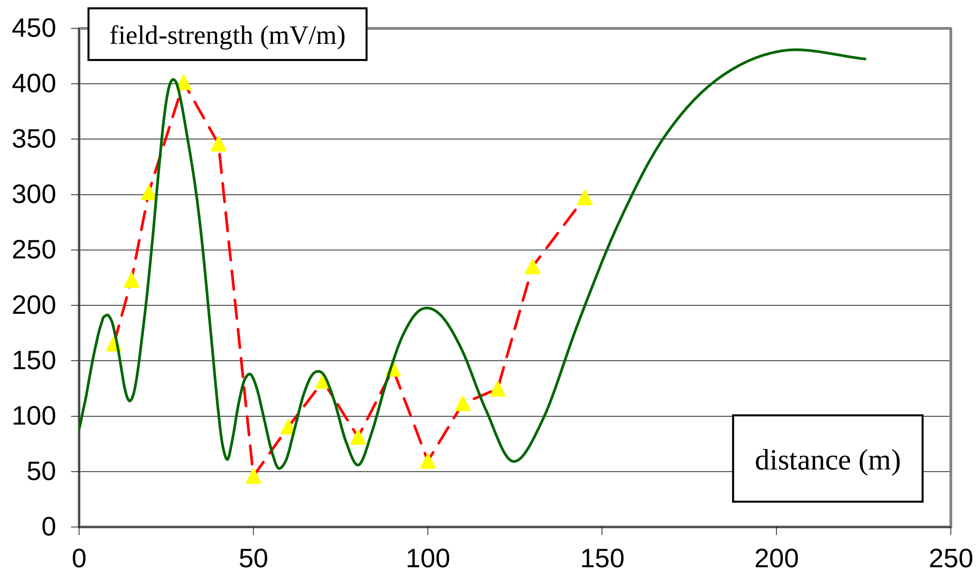
measurement points near radio base stations in seven African countries Rowley, Joyner and Marthinus 2014. Over the period 2001 to 2004 (WHO 2007 p. 30), the UK Radiocommunications Agency (now part of Ofcom) conducted radio surveys at 289 schools with base stations on or near them. At each school, measurements were made at several locations around the school looking at the GSM 900/1800 frequency bands. The field values were then compared to the ICNIRP 1998 threshold: a compliance factor of 1 would imply that the measured field just complies with the ICNIRP guidelines The highest compliance factor measured anywhere was 3.5 x 10^{-3} (= 12.2 x 10^{-6} of the power-density), with the 90% of the schools having a highest compliance factor below 2.9 x 10^{-4} (8.4 x 10^{-8} power-density) – which are very low values indeed: *de-minimis*. IARC 2013 p. 58 Fig. 1.11 specifies a cumulative distribution of exposure quotients corresponding to 3,321 spot measurements made by Ofcom at 499 sites, where public concern had been expressed about nearby base stations; the quotient values are median 8.1×10^{-6} of ICNIRP 1998 power-density, ranging from the 5th percentile 3.0×10^{-8} to 95th percentile 2.5×10^{-4}. In addition, Responding to public concerns, Ofcom published on February 2020 the results of measurements of EMF exposures close to sixteen 5G-enabled mobile phone base stations showing RF-EMF levels at a total of 22 5G sites in 10 UK cities, including also measurements for 2G, 3G and 4G. The analysis of the exposure situations shows that in urban areas the exposure levels for those living near transmitting equipment are on average between 10 and 200 mW/m^2; 100 mW/m^2 is 0.1 W/m^2, 2.2 % of ICNIRP 1998 level (4.5 W/m^2) at 900 MHz and 1.1 % of ICNIRP 1998 level (9 W/m^2) at 1,800 MHz.

9.6.2.3 Field-strength calculations versus measurements

Depending on topography, antenna downtilt and elevation pattern, the radiation signals may have a peak value in horizontal distances in the order of 80 to 120 meters from the mast (see for example Figure 9.23. Antenna beam tilt has an influence on the radiation level in the proximity of the transmitting antenna; it can be generally stated that more downtilt increases radiation levels in the proximity of the transmitting antenna (see ITU-T K.70). The exposure near the base station antenna is usually produced by the vertical antenna sidelobes that emit less power than the main beam. Nevertheless, in cases of small downtilt (e.g., 2 degrees tilt) these sidelobes may contribute the maximum exposure below and near the mast; Figure 9.25 illustrates it by measurements and calculation.
The measurements generated by ANATEL[66] were performed at RF = 1,875.8 MHz, electrical tilt 8º, mechanical tilt 0º and antenna pattern TBXLHA-6565C_1920; see the following Figure: dashed red- measured, solid green- calculated). To get the scale of the measured values: the ICNIRP 1998 (and 2020) field-strength at 400-2,000 MHz is 1.375 $f^{½}$ (MHz) ≈60 V/m, at 1,875.8 MHz. The maximal measured level is ≈0.4 V/m; *i.e.*, 0.67 % of ICNIRP field-strength threshold; 0,004 % of ICNIRP power-density limit.

[66] See Linhares, Terada and Soares 2013 Fig. 11 and Linhares A., Terada MAB. and Soares 2014 Fig. 5.

Figure 9.25 Measured (dashed) and calculated (solid) field-strength versus distance



IARC 2013 p.409 emphasises that distance to a base station is not a good proxy for exposure, due to the considerable variability in characteristics of the antennae, shielding and reflection of the waves.

9.6.2.4 Questions to be asked

Monitoring and theoretical assessments of human exposure of cellular sites around the world reveal that the exposure levels are very low, relative to ICNIRP 1998 and (ICNIRP 2020) reference levels; so, these questions may be raised:

- As there are about 8 million cellular base stations, approximately one station per thousand subscribers (see Figure 9.1 and footnote 69), do we need to enforce post-installation measurements for any base station at ground level for compliance purposes? and
- Why to monitor *ex-ante* nationally, if measurements can be made *ex-post*, after specific demand of worried citizens?

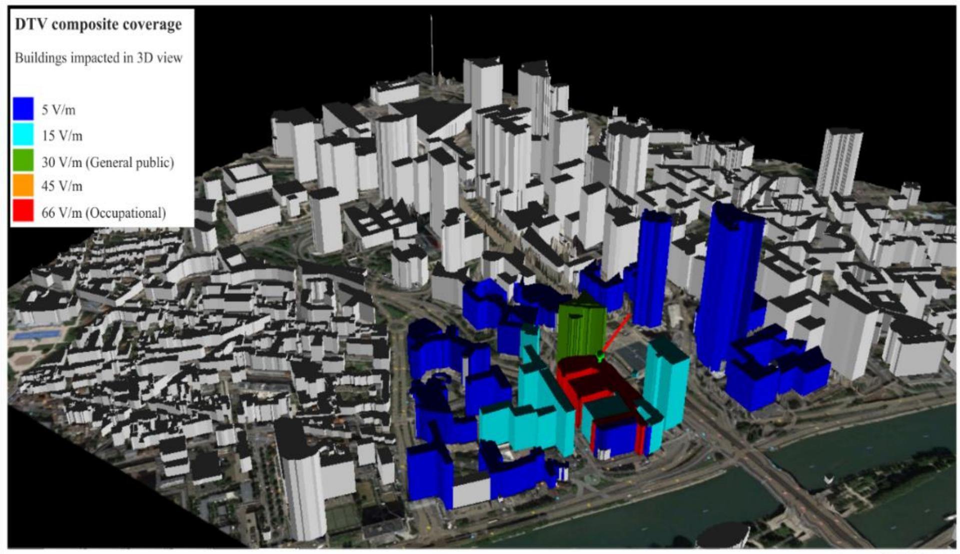
As the measurements show very low exposure levels, a ‘shadow’ question is:

- May be ICNIRP 1998 and ICNIRP 2020 reference levels are too high and administrations may reduce them?

9.6.2.5 Presenting maps of calculated field-strength around transmitters

The following two figures are based on 2019 ITU-R Report SM.2452[67], and refer to ICNIRP 1998, and ICNIRP 2020 Table 5, (see in this Document Table 9.2) for general-public and occupational exposure reference-levels. The first analysis refers to UHF Channel 22 (in ITU Region 1): 478 – 486 MHz, centre RF 482 MHz), transmitter of 60 000 Watts eirp, 60 m above ground level. At 482 MHz the electric field-strength (FS) general-public exposure reference-level equals 30 V/m: $1.375f^{1/2}$ (MHz) = $1.375 \times 482^{1/2}$. The FS (V/m) ICNIRP occupational exposure reference-level is 66 V/m: $3f^{1/2}$ (MHz) = $3 \times 482^{1/2}$. The following Figure (SM.2452 Figure 3) depicts buildings impacted in 3D view.

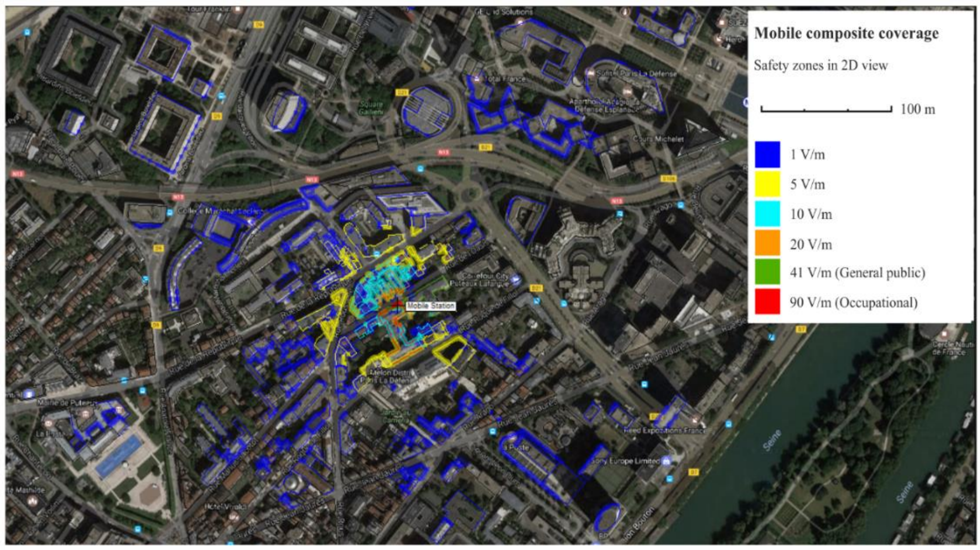
Figure 9.26 Three dimensions Digital TV general-public and occupational exposure-contours



Report SM.2452-03

The second assessment is at 900 MHz, 30 meters above the roof, for maximum downlink power of 100 W and antenna gain (including losses) 17 dBi, eirp is 5 kW, the receiver 1.5 m AGL. The ICNIRP general-public reference-level is 41 ($1.375f^{1/2} = 1.375 \times 30$) V/m, and the occupational reference-level is 90 V/M: $3f^{1/2}$ (MHz). The FS scales are 1, 5, 10, 20, 41 (general-public) and 90 (occupational) V/m. The following Figure (SM.2452 Figure 4) depicts the buildings impacted.

Figure 9.27 Two dimensions satellite view of cellular exposure distances



Report SM.2452-04

[67] 'EMF measurements to assess human exposure'. Figures were prepared by ATDI tool HTZ communications

9.7 RF Hazards limits and their impact on mobile network planning

9.7.1 *Excessive exposure limits affect network planning*

Stringent policies, regulations and approaches affect broadcasting and mobile network planning. Protest movements cause important delays in the roll-out of latest cellular technologies. If at most of investigation points the measured signal is less than 1% ICNIRP 1998 (and 2020) power-density level, what is the problem? The planning problem arises when people reside near the planned antenna. Administrative calculation of the horizontal safety-distance refers to worst-case scenario: usually assumes free-space loss and disregards the attenuation of antenna gain in elevation. Co-location of several emitters increase the specific safety-distance and restrict mast construction near buildings. Moreover, countries (e.g., Switzerland) reduce by 100 the power-density level and impose difficulty to the cellular base stations' planning. Decreasing the power-density threshold by 100, and decreasing the field-strength threshold by 10 increase the safety-distance by 10, for the same emission parameters; see equation (9.7). The conclusion: it would probably be very difficult to achieve exposure values lower than 100 mW/m^2 (=6.14 V/m) without substantial economic consequences.

Lower RF exposure limits enforce to decrease the $eirp$, in order to reduce the power-density (and field-strength) near the station, or to extend the distance of the mast from the public; these constraints harm the optimal planning and siting of base stations and antennas.

French simulations on 2G and 3G, see ANFR Rapport annuel 2013 p. 48, have shown that a reduction in exposure from 61 V/m to 0.6 V /m[68] will sharply deteriorate the coverage network and quality of service, in particular in-door ; in average 82% less interior coverage in Paris center, less coverage 44% in Grenoble and 37% in Grand-Champ. Higher levels of exposure were tested (1 V/m in Paris and 1.5 V/m in Plaine-Commune) and resulted in degradation of coverage inside buildings (losses of 60-80% in Paris centre and 30-40% in Plaine-Commune). To complete these results, simulations of antenna reconfiguration were conducted in seven cities in France, to estimate the additional number of antennas keeping the 0.6 V/m exposure threshold. The conclusion is that the number of sites would be multiplied at least by three; if taking into account also capacity, quality of service, traffic control and access, the factor will expand above three.

Some administrations and municipalities determine minimum range close to sensitive areas of concern, such as schools, hospitals, apartment buildings, children's playgrounds and permanent workplaces; those restrictions add limitations to the network planning. Note that using the phone in the areas of good reception also decreases self-exposure, as it allows the phone to transmit at reduced power (WHO 2011). In addition to the cellular antenna planning restrictions, lowering ICNIRP thresholds worsen the measurement and enforcement of the signals.

Lowering the down-link effective power, to reduce RF exposure from the base station, imposes additional sites/masts, in order to preserve the quality of service. More transceivers sites, each with lower RF emission power, reduce the human exposure levels from the fixed base stations (as down-link radiation is decreased) and the up-link handsets emissions (as they are closer to the base station and transmit less power). However, due to regulatory limitations, derived from public fears of cellular base stations, it is difficult to construct additional cellular (and broadcasting) masts. Mazar 2009 (Table 4-2 p. 110) compares and contrasts the e-Communications in EU and *Comunidad Andina de Naciones* (CAN): EU and CAN in South America define the RF spectrum as ‘scarce resources’; however, CAN adds also the physical facilities, as ‘scarce resources’.

[68] 40 dB attenuation: a factor of 100 in field-strength and 10,000 in power-density.

9.7.2 *Handling low exposure thresholds by additional cellular antennas or additional RF Spectrum*

In average, roughly every 1,000 subscribers need one cellular mast[69]. The public and cellular operators are much interested in coverage and capacity of the cellular networks. For a given network (technology, number of sites, RF spectrum, quality of service), better coverage is achieved by transmitting at higher effective power (for both down-link and up-link channels); installing base stations at higher altitude above ground level and using lower radio frequency decrease propagation loss and improve coverage. For the same propagation reason, lower frequencies are preferred for rapid roll-out, as less cellular base stations are needed. But the available RF bandwidth is reduced at lower RF; for example, compare the FDD: GSM/UMTS 900 MHz band (39x2 MHz[70]), versus the UMTS 2,100 MHz band (60x2 MHz[71]) and 5G (3.5 GHz: 24.25–27.5 GHz). Furthermore, due to extended propagation loss, higher frequencies decrease interference from neighbouring sites, to enable installation of more base stations and enhance capacity. The idea of cellular is to get more capacity not by more RF spectrum, but rather by more sites; so, additional sites solve traffic and throughput problems. Grace D. et al. 2009 do emphasise in green radio the direct trade-off between bandwidth and power (energy) efficiency 'we should strive to maximize the bandwidth usage, if we wish to minimize power usage (energy resources)'.

Only the most loaded sites need extra capacity[72]. In urban areas the limiting factor is the system capacity, while the coverage problems are dominant in rural areas. The major part of the system cost resides in the core of the system, where the limiting factor is capacity; this implies that in urban areas the major design factor is frequency reuse based on capacity determinant signal to interference (S/I), rather than on signal to noise (S/N), for coverage[73].

Higher data rates oblige more RF spectrum, reduce the range achievable by the base station (WHO 2007 p.25-6 and155) and enforce in urban areas denser base stations. An alternative solution to the capacity problem and additional cellular sites in urban areas is supplementary RF spectrum for the cellular operators. However, around the world, the RF Spectrum of cellular systems is the scarcest, only comparable to the 87.5–108 MHz, FM radio broadcasting, known as Band II internationally. As additional spectrum, sharing (network, planning, base stations and RF spectrum) also reduces the number of sites and human-hazards (?); more active sharing (including shared RF) saves spectrum, but may decrease competition.

The data explosion[74] in the cellular demand requires supplementary cellular infrastructure mainly in industrial, commercial and dense urban zones to accommodate traffic increase; therefore, more RF radiation and human exposure. Additional base stations and RF spectrum contribute more capacity and increase human exposure. The U.S. adopts liberal policies to facilitate wireless infrastructure deployment and collocations; see FCC Report and Order 14-153 Wireless Infrastructure.

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[69] Due to the large numbers, India provides good statistics. according the data of the Ministry of Communications and Information Technology, Department of Telecommunications (DoT), on 31st March 2013 service area wise in India, the number of wireless subscribers was 867,803,583 and the number of base stations was 746,602: 0.86 pro mil; see also India TRAI 2013 pp. 1,10 and 13; on 30 June 2013 service area wise in India, the number of wireless subscribers was 873,362,533.

[70] RF band 876-915 MHz up-link and 921-960 MHz down-link, including the GSM-R and extended GSM bands.

[71] RF band 1,920-1,980 MHz up-link, 2,110-2,170 MHz down-link; in addition UMTS TDD operates at 1,900-1,920 and 2,010-2,030 MHz.

[72] The dense-urban sites are separated about 300 meters, while rural are distanced more than 900 meters apart; see Report ITU-R M.2290 table A.7 'assumed cell area per radio environment'. When data defines the traffic, as a rule of thumb: about 80% of sites carry 20% of traffic, and 50% of sites carry 5% of traffic.

[73] The urban cellular system is interference-limited, not noise limited, and it operates at the minimum signal-to-interference-plus-noise ratio (SINR) or signal-to-noise-plus-interference ratio (SNIR) possible for a given quality. The base stations are built for a well contained coverage, not for maximal coverage, because overlap involves interference.

[74] Expanding the supply (coverage and capacity) also increases the demand of cellular broadband services.

9.7.3 *Trial to Quantify RF versus Sites*

9.7.3.1 Theory

The cellular signals are fading channels. Based on Shannon theorem and on the information theory of fading channels, Biglieri E., Proakis J. and Shamai (Shitz) S. October 1998 emphasize capacity, as the most important performance measure. Intuitively, it is clear that more RF reduces the number of sites! In order to quantify the relation between the site numbers and the RF spectrum, numerical simulations for different scenarios (including propagation analysis of obstacles and fading) are needed. Such quantitative analysis might be performed using the simulation framework developed for heterogeneous networks; see Tsalolikhin et al. 2012. The statistical models of fading channels, to analyse cellular networks, are beyond the scope of this chapter.
The maximum channel capacity for each communications link in a given network is derived from Shannon Hartley monumental paper (Shannon 1948 p. 43, theorem 17), relating *c*apacity (bit/s), RF *b*andwidth (Hz) and the *s*ignal to *n*oise (dimensionless) ratio:

$$c = b \times log_2 \left(1 + s / n\right) \tag{9.17}$$

The Shannon equation (9.17) is a fundamental theoretical as well as practical tool; it shows a trade-off between bandwidth b and power s: the capacity increases linearly with the increase bandwidth b, but only logarithmically with the increase in power s (Grace D et al. 2009). Two significant works in Scott, Pogorel and Pujol employ Shannon Hartley trade-off. Carter (2013 pp.41-62) apply trade-offs between permissible signal strength and allotted channel widths; Yuguchi (2013 pp. 63-76) emphasises the trade-off between investing in better equipment (in order to effectively improve the signal-to-noise ratio) versus investing in more or better spectrum.

9.7.3.2 Quantification: RF versus Sites

The following analysis to quantify that additional RF reduces the number of cellular sites is simplistic; as Shannon capacity equation relates mainly to a fixed Gaussian channel, but the mobile radio link is a faded link[75]. The first part of the Shannon equation (9.17) links the channel capacity c and the assigned RF Spectrum b; c depends directly on b.
At the $\log_2$ part of the Shannon equation (9.17), decreasing the number of sites reduces the overall *signal* at the corresponding locations, as the distances to the base stations increase[76]. Therefore, staying with the same *capacity*- less sites (reduced s) can be compensated by more frequency *band* (b). It is possible to aim to the Shannon Hartley capacity limit, by adding RF spectrum (b) and decreasing number of sites (s/n): b is increased and s/n is reduced (the opposite is also true- more sites, less RF spectrum); thus, without harming the network's maximum capacity (c) and quality of service.
Increasing the channel bandwidth b and decreasing the s/n will not necessarily reduce power at down-link and up-link signals and human exposure from specific base station and handset; as the increase of RF spectrum may oblige increase in power, to preserve power per Hz. In all cases, adding cellular sites increases coverage and capacity, and decreases the RF exposure

[75] The Shannon equation refers to a white noise and to an unlimited code and symbol length; data application that dominates the advanced cellular generations may have different optimization rules. However, when many neighbours interfere, the law of large numbers applies (not the case of one dominant interferer), and the noise assumption is Additive White Gaussian Noise (AWGN).
[76] Noise n is also dependent of the sites' density; in urban area, n is dominated by neighbour cell interference, not thermal noise.

from (specific base station and) handsets. However, people still dislike cellular masts near them. Important to note that, the noise n also depends on the basic RF bandwidth b as $n = n_0 \times b$; where n_0 denotes the noise[77] spectral density; noise power per Hz; energy, in Joule units.

To provide some evidence, the calculation is carried for cities, where capacity is dominant, and $s/n < 1$. In urban scenario s/n is typically small. The LTE reference signal received quality (RSRQ) quantifies the capacity; the user equipment UE measures this parameter as reference signal. Values higher than -9dB guarantee the best subscriber experience; the range between -9 and -12dB can be seen as neutral with a slight degradation of quality of service.

Given b is large and s is small ($n_0 \times b >> s$), the maximum capacity of the channel is calculated after transferring $\log_{10}$ to $\log_e$ (defined as ln):

$$c = b \times log_2\left(1 + \frac{s}{n_o\, b}\right) = \frac{1}{\ln 2} b \times \ln\left(1 + \frac{s}{n_o\, b}\right) \tag{9.18}$$

For $n_0 \times b >> s$, by using Taylor series, the ultimate data rate Shannon limit equals:

$$c = \frac{1}{\ln 2} b \times \left(\frac{s}{n_o\, b} - \frac{1}{2}\left(\frac{s}{n_o\, b}\right)^2 + \frac{1}{3}\left(\frac{s}{n_o\, b}\right)^3 - \frac{1}{4}\left(\frac{s}{n_o\, b}\right)^4 + \ldots\right) \approx \frac{b}{\ln 2}\left(\frac{s}{n_o\, b}\right) \approx \frac{1}{\ln 2} \times \left(\frac{s}{n_o}\right) \approx 1.44 \times \left(\frac{s}{n_o}\right) \tag{9.19}$$

When $n_0 \times b >> s$, equation (9.19) reveals that the capacity c is limited by power s (linearly) and noise density n_o: decreasing s/n_0 (less sites) is compensated linearly by increasing b. To exemplify: multiplying the RF spectrum (b) to the operator by 4 ($b_2 = 4b_1$) results in decreasing the number of base stations, so the wanted signal ($s_2 = s_1/4$) may be divided by 4.

9.8 Policies and mitigation techniques to reduce the human exposure

9.8.1 *Policies to reduce the human exposure to RF radiation*

Derived from the precautionary-principle, these are polices to reduce human hazards:

- Follow the existing ICNIRP 2020 limits from stations and cellular handsets at the national level and across the country. These exposure limits are the current international scientific consensus. The tolerability of the human body to RF radiation is independent of geography or political borders: there is no technical justification for different national exposure levels. Cellular networks are not local; there is no engineering reason for different exposure levels among cities inside the country; the definition of exposure limits should be national[78], and outside the competency of municipal or provincial councils;
- Europeans may follow the council of Europe, Resolution 1815 (2011) *considering* §5 and *recommendation* § 8.5.4, apply the:
    - ALARA (as low as reasonably achievable) principle, covering both the so-called thermal effects and the a-thermic or biological effects of electromagnetic emissions or radiation; see also *recommendations* § 8.1.2 and 8.4.3; and
    - The precautionary-principle, when scientific evaluation does not allow the risk to be determined with sufficient certainty. Given the context of growing exposure of

[77] Assuming that the noise is 'white'. The thermal nose is definitely white; interference from wideband digital signals seems also white.

[78] The city-model seems not to have been effective under any point of view. It has prevented the development of networks, with no evident health benefit for public health; at the same time, it has not settled down the controversies and probably has not reduced public concern (WHO 2007 p.148).

the population, in particular that of vulnerable groups such as young people and children, there could be extremely high human and economic costs if early warnings are neglected; see also *recommendation* § 8.2.1;

- Introduce clear labelling indicating the presence of microwaves or electromagnetic fields, the transmitting power or the SAR of the device and any health risks connected with its use[79];
- Prioritize the alternative cable and satellite telecommunications, in order to reduce off-air TV, fixed wireless access emissions, wireless internet router and broadband applications;
- Promote cellular sites' co-location[80] passive (same site, mast and antenna) and even active sharing (same transceivers and frequencies) among operators, in order to reduce the number of the cellular base stations and in general[81] the human exposure;
- Do not limit construction of masts near sensitive places, as the individual exposure from the handsets increases, with fewer base station antenna, due to handset power growth[82].
- Inform the public transparently about existing and expected exposure values, by performing simulations. For the cell phones: provide good visible publication of the SAR values;
- Theoretically assess every base station to assure that general public exposure is lower than ICNIRP 2020 reference levels; measure upon request; try to software monitor the exposure and emitted power 24 hour a day 365 days a year; and
- Solve the property devaluation problem.

9.8.2 *Mitigation techniques to decrease the radiation level*

Enclosed techniques to reduce the human exposure:

- Restrict access to areas where the exposure limits are exceeded. Physical barriers, lockout procedures and adequate signs are essential; workers can use protective clothing (Recommendation ITU-T K.52);
- Increase the antenna height. The distances to all points of investigation are increased and the radiation level is reduced. Moreover, additional attenuation to the radiation is achieved due to the increase of off-boresight elevation angle and decrease of transmitting antenna sidelobe (K.70);
- Increase the antenna gain (mainly by reducing the elevation beam width), and consequently decrease the radiation in the direction accessible to people. The smaller vertical beam width may be used to reduce the radiation level in close proximity to the antenna. Moreover, the same value of the eirp can be achieved by a low power transmitter feeding high gain antenna or by high power transmitter feeding low gain antenna. As far as the protection against radiation is concerned, a much better choice is to use the low power transmitter feeding the high gain antenna. (K.70); and
- Minimize the base station transmission to the minimum needed to maintain the quality of the service, as quality criterion. Decrease the transmitter power and consequently decrease linearly the power-density in all the observation points. As this mitigation technique reduces the coverage area, it is used only if other methods cannot be applied (K.70).

[79] See the council of Europe, Resolution 1815 recommendation § 8.2.3.
[80] Co-location and national roaming increase human exposure near the specific site; but the general public exposure is reduced.
[81] Taking also into account the also national roaming among operators
[82] Regards minimum distances from buildings and inhabited areas 'Contrary to the general perception of the public, such measures increase, rather than decrease, the average environmental level of EMF' (WHO 2007 p.148).

9.8.3 *Myths and realities*[83]

The public hypersensitivity and electrophobia lead to some myths which are contrary to physical realities. The following is a summary of these situations:

- Myth: the construction of a site antenna in one's neighborhood should be of RF human exposure concern to people of that neighborhood.

Reality: quite the opposite. As use of handsets is total, the limiting factor in terms of EMF exposure is the transmissions from the handset (up-link). This is the case in view of its physical proximity to the user's body. The handset transmissions are power controlled, such that the handset does not transmit higher power than what is necessary to maintain reliable communications. Closer to the site the handset transmits less power;

- Myth: the higher the number of the transmitting sites in a given area the higher the EMF exposure.

Reality: not true. In reference to the exposure from the handset see the above; due to the profusion of sites, the handsets are closer to their corresponding base station and emit less. For radiation from the site antenna, the transmission levels are such that they should allow quality of service at the cell boundaries. The power-density attenuates as the square of distance in free space and with a higher exponent (typically around 4 for ground waves) resulting in higher levels at the inner areas of the cell. The smaller the cells the smaller is that extra exposure levels in the inner parts of the cell;

- Myth: the larger the dimensions of the cell site and antennas, the higher the exposure.

Reality: not true. Antennas are made big in order to get higher gains of main beams. As a result the field-strength (and power-density) in the area close to the antenna is reduced; it is achieved due to the sidelobe in elevation; and

- Myth: an antenna erected on the roof causes maximum exposure inside the building underneath.

Reality: not true. The antenna transmits horizontally (or some small downtilt) such that directly underneath, the transmissions are much reduced. Moreover, a concrete roof is a quite strong attenuator of EMF.

[83] I gratefully acknowledge the contribution by Dr. Reuven Meidan.

9.9 IMT-2020 (5G) and EMF

9.9.1 *ITU-R WRC-19 Identification of IMT (5G) frequency bands*

Following the 2020 edition of the ITU Radio Regulations (RR) published on 15 September 2020 and the proposed revision of Recommendation ITU-R M.1036 that is currently discussed within ITU-R[84], the following frequency bands are identified in the ITU RR to deploy IMT.

Table 9.14: ITU RR 2020 Footnotes identifying the band for IMT

Band	Footnotes identifying the band for IMT		
	Region 1	**Region 2**	**Region 3**
450-470 MHz	**5.286AA**		
470–698 MHz	**-**	**5.295, 5.308A**	**5.296A**
694/698–960 MHz	**5.317A**	**5.317A**	**5.313A, 5.317A**
1 427–1 518 MHz	**5.341A, 5.346**	**5.341B**	**5.341C, 5.346A**
1 710–2 025 MHz	**5.384A, 5.388**		
2 110–2 200 MHz	**5.388**		
2 300–2 400 MHz	**5.384A**		
2 500–2 690 MHz	**5.384A**		
3 300–3 400 MHz	**5.429B**	**5.429D**	**5.429F**
3 400–3 600 MHz	**5.430A**	**5.431B**	**5.432A, 5.432B, 5.433A**
3 600–3 700 MHz	**-**	**5.434**	**-**
4 800–4 990 MHz	**5.441B**	**5.441A, 5.441B**	**5.441B**
24.25–27.5 GHz#	**5.532AB**		
37–43.5 GHz#	**5.550B**		
45.5–47 GHz#	**5.553A**	**5.553A**	**5.553A**
47.2–48.2 GHz#	**5.553B**	**5.553B**	**5.553B**
66–71 GHz#	**5.559AA**		

revised at WRC-19

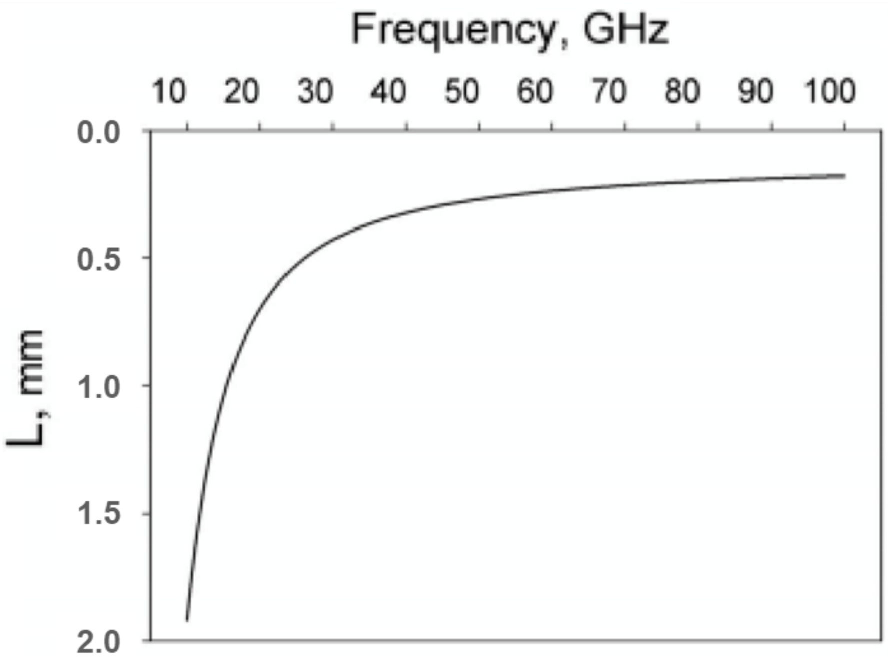
9.9.2 *mmWaves mostly absorbed in outer skin layers*

ICNIRP 2020 specifies at 6 GHz (5 cm wavelength), where EMFs penetrate deep into tissue (and thus require depth to be considered), it is useful to describe EMF terms of SAR. Conversely, above 6 GHz, where EMFs are absorbed more superficially (making depth less relevant), it is useful to describe exposure in terms of the density of absorbed power over area (W/m^{-2}). At 6 GHz, most of the absorbed power is within the cutaneous tissue. Above 6 GHz, skin surface heating is dominant. ICNIRP 2020 specifies an additional exposure level, for square 1 cm^2 averaging areas, applicable for EMFs with frequencies of >30 to 300 GHz, to account for focused beam exposure.

The following Figure[85] depicts: energy penetration depth into the skin at 6 GHz is approximately 4 mm; penetration decreases monotonically with increasing RF. At 300 GHz, energy penetration depth is approximately only 0.12 mm[86].

[84] See 'Background Paper, ITU regional forum for Europe: 5G strategies, policies, and implementation' p. 16
[85] See © 2019 Glatte, Buchmann, Hijazi, Illigens and Siepmann Glatte et al., Sept 2019
[86] see also IEEE C95.1-2019 p. 69, A.2.5.4

Figure 9.28: IEEE C95.1 (2019) versus ICNIRP (2020) whole-body and local exposure-limits



However, the ICNIRP 2020 Table 10, see enclosed, details different numbers:

Table 9.15: (ICNIRP Table 10) penetration depth of human skin tissue (dermis), for frequencies 6 to 300 GHz

Frequency (GHz)	Relative permittivity	Conductivity (S/m)	Penetration depth (mm)
6	36	4.0	8.1
10	33	7.9	3.9
30	18	27	0.92
60	10	40	0.49
100	7.3	46	0.35
300	5.0	55	0.23

9.9.3 *Impact of IMT-2020 (5G) on EMF*[87]

The first 5G NR (New Radio) version was officially released at the 78th plenary meeting of the 3GPP RAN (Radio Access Network) on 21 December, 2017, which is the first commercially deployable 5G standard in the world. At present, the 5G frequency range defined by 3GPP is divided into Frequency Range 1 (FR1) and Frequency Range 2 (FR2). FR1 is usually called sub 6 GHz, below 6 GHz. At present, 3.5 GHz is one of the mainstream bands of 5G applications; however, 3GPP has also defined other available bands to facilitate flexible deployment. FR2 range is mainly high frequency, which is commonly referred to as millimeter wave. Its penetration ability is weak, but bandwidth is sufficient, and there is no interference source. Its spectrum is clean, and it will be widely used in the future.

Due to the characteristics of Multiple-Input Multiple-Output (MIMO) and millimeter-wave technologies used in the 5th generation mobile communication system, it is urgent to evaluate its RF EMF levels. A pioneer study[88] indicated that the maximum time-averaged power per beam direction was found to be well-below the theoretical maximum and lower than what was predicted by the existing statistical models.

[87] See ITU-D Draft Report of Question 7/2 to WTDC, Section 4.3

[88] D Colombi, P Joshi, B Xu, F Ghasemifard, V Narasaraju and C Törnevik (2020). Analysis of the Actual Power and EMF Exposure from Base Stations in a Commercial 5G Network. Applied Sciences (35), 10:5280.

MIMO technology refers to the simultaneous use of multiple transmit and receive antennas, so that signals can be transmitted and received through multiple antennas at the transmitter and receiver, thereby improving the communication quality. Without increasing spectrum resources and antenna transmit power, it multiplies system channel capacity, showing obvious advantages, and is regarded as the key technology of the next generation mobile communication.

A model for time-averaged realistic maximum power levels for the assessment of radio frequency (RF) EMF exposure for 5G Radio Base Stations (RBS) employing massive MIMO is proposed[89]. The model is based on a statistical approach and developed to provide a realistic conservative RF exposure assessment for a significant proportion of all possible downlink exposure scenarios (95th percentile). Factors, such as RBS utilization, time-division duplex, scheduling time, and spatial distribution of users within a cell are considered. The model is presented in terms of a closed-form equation. For an example scenario corresponding to an expected 5G RBS product, the largest realistic maximum power level was found to be less than 15% of the corresponding theoretical maximum. For far-field exposure scenarios, this corresponds to a reduction in RF EMF limit compliance distance with a factor of about 2.6. Results are given for antenna arrays of different sizes and for scenarios with beam forming in both azimuth and elevation.

It has been agreed that 5G operating above 10 GHz (6-10 GHz as transition frequency for local exposure) will not utilize Specific Absorption Rate (SAR) for partial body exposure but power density as the basic restriction, because it is difficult to determine a meaningful volume for SAR evaluation at very low penetration depth. However, ICNIRP kept whole-body average SAR limits as an additional basic restriction for whole body exposure up to 300 GHz. At present, ICNIRP Guidelines use incident power density as reference levels, which do not take the reflection or transmission of energy on the boundary into account, nor does it consider the heat transfer between tissues or between tissues and environment. The ICNIRP (2020) guidelines also introduce absorbed power density as a basic restriction at higher frequencies (>6 GHz). In the future, temperature may be regarded as an acceptable parameter to prove the safety of radiation (as in the magnetic resonance imaging industry), because it is more relevant to actual damage.

Zhao et al.[90] studied RF EMF exposure of phased array for mobile devices operating at 15 GHz and 28 GHz. Thors et al.[91] conducted a series of simulations on RF EMF exposure of array antenna in 5G mobile communication equipment between 10 GHz and 15 GHz. In order to meet the main RF EMF exposure criteria, the maximum transmit power of the array antenna used in user equipment and low-power wireless base station in 5G mobile communication system is investigated, taking into account the factors such as frequency, array size, distance from human body, scanning range and array topology. The results are of great value to the design of mobile communication systems using array antennas with beam forming capability. In order to allow greater power levels, it is necessary to direct the transmitted energy away from the human body through implementable technical solutions. According to the applicable RF-EMF exposure standard, the maximum power transmit level and the maximum equivalent omnidirectional radiation power of 5G mobile communication systems may change greatly. This inconsistency may lead to different access conditions in different markets.

[89] B. Thors, A. Furuskär, D. Colombi and C. Törnevik, (2017). Time-averaged realistic maximum power levels for the assessment of radio frequency exposure for 5g radio base stations using massive mimo. IEEE Access, 5, 19711-19719.
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9.9.4 *IEC Standards to measure RF-EMF*

Those are International Electrotechnical Commission (IEC) standards, most relevant also to 5G:

- IEC/IEEE 62209-1528 (2020): Measurement procedure for the assessment of specific absorption rate of human exposure to radio frequency fields from hand-held and body-worn wireless communication devices - Part 1528: Human models, instrumentation and procedures (Frequency range of 4 MHz to 10 GHz)
- IEC 62232 (2017): Determination of RF field strength, power density and SAR in the vicinity of radiocommunication base stations for the purpose of evaluating human exposure
- IEC TR62630 (2010): Guidance for evaluating exposure from multiple electromagnetic sources
- IEC TR63170 (2018): Measurement procedure for the evaluation of power density related to human exposure to radio frequency fields from wireless communication devices operating between 6 GHz and 100 GHz
- IEC/IEEE 62704-1 (2017): Determining the peak spatial-average specific absorption rate (SAR) in the human body from wireless communications devices, 30 MHz to 6 GHz - Part 1: General requirements for using the finite difference time-domain (FDTD) method for SAR calculations
- IEC/IEEE 62704-2 (2017): Determining the peak spatial-average specific absorption rate (SAR) in the human body from wireless communications devices, 30 MHz to 6 GHz - Part 2: Specific requirements for finite difference time domain (FDTD) modelling of exposure from vehicle mounted antennas
- IEC/IEEE 62704-3 (2017): Determining the peak spatial-average specific absorption rate (SAR) in the human body from wireless communications devices, 30 MHz to 6 GHz - Part 3: Specific requirements for using the finite difference time domain (FDTD) method for SAR calculations of mobile phones
- IEC/IEEE 62704-4 (2020): Determining the peak spatial-average specific absorption rate (SAR) in the human body from wireless communication devices, 30 MHz to 6 GHz - Part 4: General requirements for using the finite element method for SAR calculations

Those are IEC/IEEE ongoing standards, most relevant also to 5G:

- IEC / IEEE 63195-1:Measurement procedure for the assessment of power density of human exposure to radio frequency fields from wireless devices operating in close proximity to the head and body – Frequency range of 6 GHz to 300 GHz, expected in Aug. 2021
- IEC/ IEEE 63195-2: Determining the power density of the electromagnetic field associated with human exposure to wireless devices operating in close proximity to the head and body using computational techniques, 6 GHz to 300 GHz, expected in Aug. 2021.

9.10 Conclusions

The global regulations and guidelines of the general-public and occupational exposure limits are continuously reviewed by experts. The summary of IARC 2013 p.409 'it is likely that not all mechanisms of interaction between weak RF fields, with the various signal modulations used in wireless communications, and biological structures have yet been discovered or fully characterized'.

The national limitations to radio frequency human exposure are becoming more stringent, due to societal concerns and electromagnetic hypersensitivity. Municipalities and national administrations strive to lower thresholds. Worldwide standards and universal thresholds on human-hazards will avoid a Babylon tower of standards that confuse suppliers, operators and users. The globalization and harmonization should lead to the adoption of the universal levels of ICNIRP 2020. Furthermore, there is no technical justification for different exposure levels. The underlining factor of the RF exposure of humans is the subscriber's handset and not the base antenna. Wireless communications are vital. Due to the high number of people exposed to RF radiation, while scientific uncertainty on harmful effects still exists, implementing the precautionary-principle is warranted and reasonable; efforts are needed to reduce the human exposure to RF, as low as reasonably achievable.

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