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Radio Frequency Electromagnetic Exposure: A Public Safety Assessment

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Abstract—**Nowadays, with the impressive development of cellular networks and other wireless communication technologies, the public concerns about possible health effects of exposure to electromagnetic radiations are increased. In this paper, we investigate some radio frequency (RF) exposure levels measured in the urban areas. These measurements include all RF radiations of various electromagnetic wave sources including those from broadcasting stations to cellular base stations. The exposure levels are incident power density values measured during 18 months at 930 locations distributed over 7 major cities of Iran. These results are compared with the relevant guidelines of non-ionizing radiation given in the Iran national standard no. 8567, to confirm that the measured radiation exposure levels are satisfactorily below the defined limits.**

Keywords: Non-ionizing radiation, radio frequency exposure, exposure level, public safety, incident power density.

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I. Introduction

Throughout the recent years, with the rapid development of radio communication systems and mobile networks, the issue of potential harmful effects of radio frequency (RF) electromagnetic exposure on human health has raised many public concerns. The recent generations of mobile communications require denser network architecture to support the required bit rate of new services and respond to the growing traffic demand of mobile users. Small cells can afford this densification by enabling deployment of many low-power base stations in the concentrated areas. The vast number of base stations together with the introducing new technologies such as the internet of things (IoT), has intensified previous public concerns about the amount of RF exposure and its possible and unknown health effects.

According to the scientific evidences, electromagnetic fields create various biological effects on human body. These effects can be divided into thermal and non-thermal corresponding to the frequency and power/intensity specifications of the incident field [1]. The thermal effects occur in the frequency range of 100 kHz to 300 GHz, cause an increase in the body temperature. However, the non-thermal effects created by long-term and repeated radiation may cause electromagnetic sensitivity or neurological disorders. Electromagnetic fields have also been tested or used in clinics for medical applications including pain mitigation, muscle rehabilitation, nerve stimulation, bone repair, osteoarthritis therapy, electro acupuncture, wound healing and drug delivery [2]-[5].

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Numerous studies have been conducted in order to investigate the adverse biological effects of electromagnetic waves. Some of these studies have focused on determining the relationship between cell phone use with brain tumor risk in adults and children [6]-[10]. Moreover, the effects of electromagnetic radiation on the nervous tissues have also been a subject of many investigations [11]-[14]. A number of studies have examined the effect of electromagnetic radiation on cardiovascular system [15] and [16]. Furthermore, the issue of electromagnetic field exposure on the reproductive system and fertility has been investigated in the literature [17]-[20].

In order to assess intensity of public exposure and its adverse health effects, conducting electromagnetic field measurements are necessary. Accordingly, the exposure levels should also be measured in areas accessible to the people. Then, compliance with electromagnetic field limits should be assessed, taking into account that power density and field strength aggregated from different sources [21]. These exposure limits have been established by international authorities and arisen from established biological effects. In this regard, the guidelines provided by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) have been considered worldwide by most countries as reference limits [22]. The ICNIRP guidelines provide the radiation exposure limits for different frequencies from 0 to 300 GHz and explain the short-term and long-term permanent or non-permanent exposure conditions of radio frequency electromagnetic fields. In these guidelines, the amount of exposure level is provided for two categories of occupational and the general public.

This paper, investigates the exposure levels of the general public to electromagnetic radiation originating from all radio RF emitters up to 18 GHz is in 7 cities of Iran. The recorded incident power densities are compared with the exposure limits of the general public presented by national standards.

II. Type of Electromagnetic Radiations

The term radiation refers to the energy that travels via waves or particles. The electromagnetic radiation spectrum, range from static fields to infinite frequency fields, is subdivided into two categories depending on their main effects on materials. The lower frequencies of this spectrum are categorized as non-ionizing [23]. At the higher frequencies, where the wavelength is on the nanometers and smaller scale, the radiation becomes ionizing. This means that there is sufficient energy to dislodge electrons from atoms or to eject one or several electrons from an atom to create ions. Exposure to ionizing energy increases the risk of DNA damage, associated with an increased risk for the cancer. Examples of ionizing radiation are x-rays, γ-rays and cosmic rays. Non-ionizing radiation includes a wide spectrum of frequencies and fortunately, RF spectrum that has been used in many applications of wireless communications, are located in the non-ionizing part.

III. Exposure Limits for RF Radiation

In order to determine the exposure limits of RF electromagnetic fields, it is required to identify the available scientific literature about the adverse effects of electromagnetic radiation on biological systems. The main biological effects used to establish the criteria are central nervous system stimulation, peripheral nervous system stimulation and temperature increase in tissues. Adherence to exposure limits is intended to protect people from all substantiated harmful effects of RF electromagnetic exposure. To define these limits, ICNIRP first identified published scientific literature concerning the effects of RF electromagnetic exposure on biological systems and specified which of these effects have been scientifically to be harmful to human health. This issue is important, because from ICNIRP's point of view, the announced adverse effects of RF electromagnetic fields on health should be verified independently and while having high scientific support, they should be consistent with current scientific findings so that they can be cited to determine RF exposure limits. For each of the proven effects, threshold values were determined by ICNIRP, which were derived from a conservative point of view. Determining these values was based on the relationship between the primary effects of RF exposure (such as heat) and the health effects (such as pain) to determine the appropriate level of protection. The reduction factors were then applied to the resultant thresholds to construct the exposure restriction values. These reduction factors account for biological variability in the population (e.g., age, sex), variation in baseline conditions (e.g., tissue temperature), variation in environmental factors (e.g., air temperature, humidity, clothing), dosimetric uncertainty associated with deriving exposure values, uncertainty associated with the health science, and as a conservative measure more generally [22].

The resultant exposure restriction values are referred to as “basic restrictions”. These values are related to the physical quantities that are corresponded to the RF induced adverse health effects. Some of the basic restrictions are physical quantities inside the exposed body and cannot be simply measured. Therefore, the quantities that are more simply evaluated, named “reference levels” have been derived from the basic restrictions to enable a more-practical assessment of compliance with the guidelines. Reference levels have been derived such that under worst-case exposure conditions, they will cause similar exposures to those specified by the basic restrictions. Specific absorption rate (SAR) (in W kg^{-1}), absorbed power density (in W m^{-1}), specific energy absorption (in J kg^{-1}) and absorbed energy density (in J m^{-2}) are the quantities used in ICNIRP guidelines to specify the basic restrictions. However, the reference level quantities relevant to these guidelines are incident electric field strength (in V m^{-1}), incident magnetic field strength (in A m^{-1}), incident power density (in W m^{-2}), plane wave equivalent incident power density (in W m^{-2}), incident energy density (in J m^{-2}) and plane-wave equivalent incident energy density (in J m^{-2}), all measured outside the body.

TABLE I. INCIDENT POWER DENSITY REFERENCE LEVELS FOR WHOLE BODY EXPOSURE, AVERAGED OVER 30 MIN [22].

Exposure scenario	Frequency range	Incident power density (W m^{-2})
Occupational	0.1 – 30 MHz	not applicable
	30 – 400 MHz	10
	400 – 2000 MHz	$^{*}f_M/40$
	2 – 300 GHz	50
General public	0.1 – 30 MHz	not applicable
	30 – 400 MHz	2
	400 – 2000 MHz	$f_M/200$
	2 – 300 GHz	10

* f_M is frequency in MHz .

In the ICNIRP guidelines, differences are considered between electromagnetic exposure of occupational (workers) and the general public. Workers refer to the healthy adults who are exposed to radiation due to their job and under controlled conditions. According to the training, these people are aware of the exposure of RF radiations and its possible hazardous effects and use the necessary protective equipment to deal with possible dangers. The general public refers to the people who are in different ages and health conditions. In this group, there may be vulnerable people who lack knowledge about the dangers of electromagnetic exposure or related protection methods. These differences increase the importance of applying stricter limits for the exposure of general public to protect them from any possible harmful effects of the electromagnetic waves. The permissible radiation exposure limits determined by the ICNIRP for the general public are much lower (about one fifth) than for the occupational. The incident power density reference levels of ICNIRP guideline for exposure averaged over 30 min in the case of the whole body exposure to electromagnetic fields from 100 kHz to 300 GHz are given in Table 1.

The ICNIRP guidelines are recommended by World Health Organization (WHO) and these RF electromagnetic frequency guidelines are adopted by most countries around the world. However, some countries such as Canada, Italy, Poland, Switzerland, China, Russia, France, and Belgium establish more restrictive limits than the ICNIRP ones. These countries claim to promote the precautionary principle [24], which demands lower maximum exposure limits.

In Iran, the RF exposure criteria have been introduced in a national standard with number 8567 [25]. According to this national standard, the amount of general public exposure limit in the frequency range up to 18 GHz is equal to 440 µW cm^{-2}.

IV. OVERVIEW AND ANALYSIS OF MEASUREMENTS

A. RF Measurement Methods

Recommendation ITU-T K.83 presents a guidance on how to perform long-term measurements for monitoring of RF fields in those areas that are under public concern, to demonstrate that the exposure levels are under control and under the limits [26]. The purpose of this recommendation is to represent the general public, understandable and simply available data concerning the RF field levels emitted by radio transmitters in the form of results of continuous measurement. Recommendation ITU-T K.83 defines two methods that shall be used to determine total electromagnetic exposure. These two methods are the frequency selective measurement and broadband measurement.

In frequency selective measurement procedure, the frequency range is divided into sub-ranges depending on the region. This kind of measurement procedure consists of repeated measurement cycles, each representing one measurement result for each frequency sub-range. The measurement equipment consists of an isotropic probe and a frequency selective measuring instrument, which processes the signal from the probe and indicates the value of the electromagnetic field quantity.

The broadband measuring method is appropriate in those cases where the total summation of the emissions of a specific frequency band is necessary to be measured. It allows obtaining a rapid measure of the total emission level of the band at a low cost. This broadband method should not be applied if it is essential to know the radiation levels by frequency. The instrument used for broadband measurement consists of an equipment that has a broadband probe. This measuring equipment must provide the root mean square (RMS) value of the electric field strength in order to compare the levels measured with the exposure limits [26].

The broadband measuring probes offer absolute field values, without frequency information. Therefore, it can integrate all of the emissions in the considered frequency band. Accordingly, the used broadband probe shall cover the whole band of interest and must be isotropic. By this isotropic probe, each one of the three field components must be measured feasibly at the same time to have an accurate total field result. The measuring equipment operates autonomously when it is put into operation. The field measurements should be an average of duration according to the national regulations.

In multiple frequency environment, for the exposure from several fields with different frequencies at the same time, their effect is cumulative. Accordingly, the total fraction of exposure in the desired frequency band is calculated by the summation of the fraction of exposure in all sampled frequencies and the cumulative limit across frequencies for all sources is [28]:

$$\sum_{i=100\text{ kHz}}^{300\text{ MHz}} \max\left[\left(\frac{E_{mes,i}}{E_{ref,i}}\right)^2, \left(\frac{H_{mes,i}}{H_{ref,i}}\right)^2\right] + \sum_{i>30\text{ MHz}}^{300\text{ GHz}} \frac{S_{mes,i}}{S_{ref,i}} \le 1 \quad (1)$$

where, $E_{mes,i}$ (V m^{-1}), $H_{mes,i}$ (A m^{-1}) and $S_{mes,i}$ (W m^{-2}) are the measured incident electric field, magnetic field and power density at frequency i and $E_{ref,i}$ (V m^{-1}), $H_{ref,i}$ (A m^{-1}) and $S_{ref,i}$ (W m^{-2}) are the reference level values of incident electric field, magnetic field and power density corresponding to frequency i as advised in the ICNIRP guidelines or as provided by the national guidelines. For frequencies above 30 MHz, (1) can be simplified as:

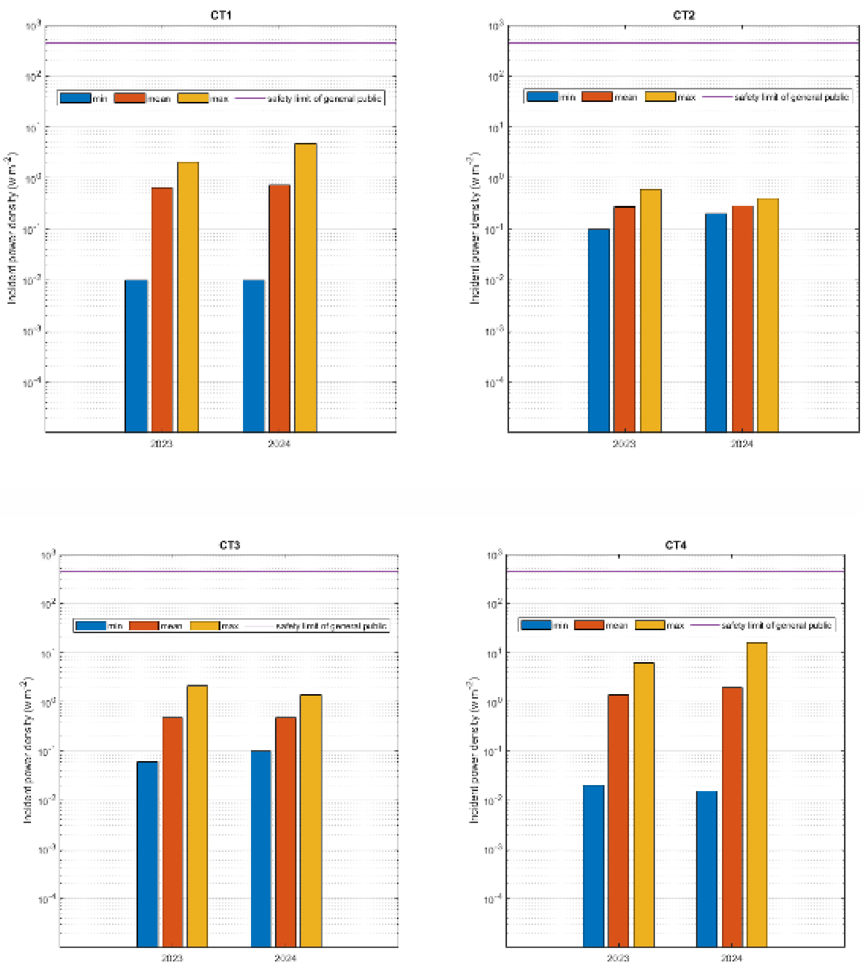
$$\sum_i \frac{S_{mes,i}}{S_{ref,i}} \leq 1 \qquad (2)$$

where $S_{ref,i}$ are provided in Table 1.

B. Analysis of Broadband Measurements

In Iran, the level of RF exposure is continuously monitored by communication regulatory authority, as one of the corresponding organizations in the field of radiation protection. In recent years, the regulator has installed fixed broadband sensors in some cities to continuously measure the amount of RF radiations. Vehicle-based or mobile radio wave intensity monitoring systems are also used in some other cities and throughout the country. Currently, the cumulative incident power densities are measured and monitored through these sensors. These incident power density measurements take into account exposure from all RF emitters include broadcasting stations and cellular base stations. The measurements collect cumulative data related to broadband electromagnetic exposure across frequencies up to 18 GHz in the urban areas. The incident power density measurements considered to analyze in this paper were recorded during 18 months (from spring 2023 to the end of summer 2024) at 930 outdoor urban locations distributed over 7 major cities in Iran. These cities are capital of different provinces located in center, north, north east and north west of Iran. Most of the measurement locations are in highly populated areas in the centers of these cities. Previously, we considered the issues of public safety assessment of RF exposure in 9 cities where the process of measurement data acquisition took place during 1 year from beginning of the spring of 2023 to the beginning of the spring of 2024 [27]. However, the measurement data collected only for 7 cities in 2024. Accordingly, in this paper we restrict our assessment to only 7 cities which their whole measurement data are available.

In Fig. 1, the minimum, mean and maximum values of the measured incident power density at the mentioned cities are presented in logarithmic scale for both 2023 and 2024 measurements and are compared with the safety limit of general public. As it is expressed in previous section, the amount of general public exposure limit is considered to be 440 µW cm^{-2} which is the lowest amount of general public radiation exposure limit in the frequency range of mobile communication. Table 2 presents the mean values of the measured incident power density at all 7 cities.



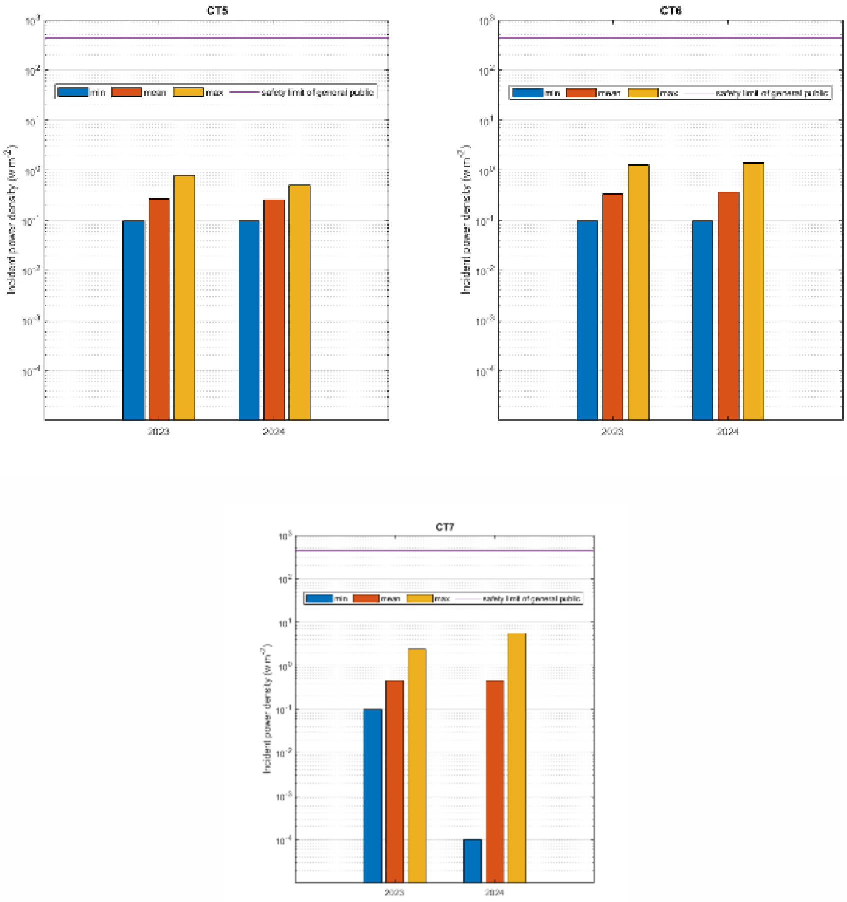


Figure 1. Minimum, mean and maximum value of measured power density the cities according to the data acquisition in 2023 and 2024.

TABLE II. MEAN VALUES OF THE MEASURED INCIDENT POWER DENSITY.

Cities	Mean values of Measurements of 2023 (μW cm^{-2})	Mean values of Measurements of 2024 (μW cm^{-2})	Total mean values of Measurements (2023 & 2024) (μW cm^{-2})
CT1	0.6529	0.7075	0.6727
CT2	0.2650	0.2740	0.2685
CT3	0.4709	0.4633	0.4676
CT4	1.3679	1.9296	1.5926
CT5	0.2675	0.2600	0.2646
CT6	0.3351	0.3683	0.3494
CT7	0.4604	0.4500	0.4564

In practice, it is usual to evaluate how many times the exposure level at any measurement point is below the safety limit. To this end, times below limit (TBL) can be expressed simply by the following equation:

$$\text{TBL} = \frac{1}{\sum_i \frac{S_{mes,i}}{S_{ref,i}}} \quad (2)$$

In other words, if the incident power density at the measurement point is multiplied by TBL, the limit value is obtained.

In Table 3 the percentage of the measurement points in accordance with different values of TBL are presented in all cities.

TABLE III. PERCENTAGE OF THE MEASURED POINTS, VERSUS THE VALUES OF TBL IN THE CITIES.

Value of TBL	Percentage of the measurement points in the cities						
	CT1	CT2	CT3	CT4	CT5	CT6	CT7
TBL<100	0.91	0	0	6.67	0	0	0.77
100≤TBL<500	37.27	0	17.14	40.00	0	7.14	13.08
500≤TBL<1000	24.54	2.31	15.71	13.33	5.38	17.14	11.54
1000≤TBL<5000	29.10	97.69	66.46	32.00	94.62	75.72	70.00
5000≤TBL<10000	7.27	0	0.714	0.67	0	0	0
TBL≥10000	0.91	0	0	7.33	0	0	4.62

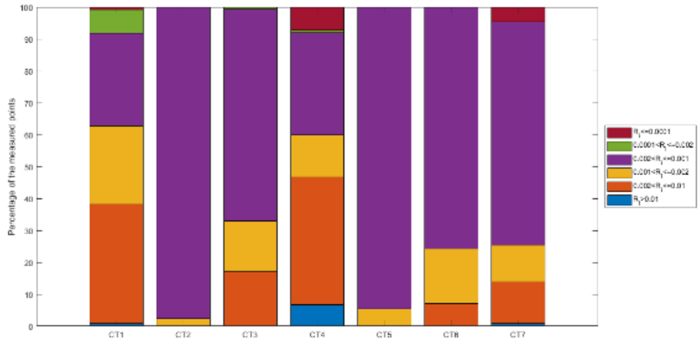


Figure 2. Percentage of the measured points, versus different value of R_i .

V. Discussion

According to Fig. 1, the measurements performed in all cities, demonstrated that the maximum level of RF-exposure does not exceed the level of 440 µW cm^{-2} established by Iran national standard reference levels. By the analysis of the measurements, the maximum value of the incident power density recorded for the cities is 15.6 µW cm^{-2}, which is 14.5 dB below the maximum allowed exposure level value of 440 µW cm^{-2}. Furthermore, the maximum value of the mean incident power density recorded for the cities is 1.93 µW cm^{-2}, which is 23.58 dB below the maximum allowed exposure level value of 440 µW cm^{-2}.

According to Table 3, the percentage of the measurement points with TBL<100 is only 0.91, 6.67 and 0.77 in 3 cities while it is 0% in the others. This means that, in the worst case, only in 6.67% of the measurement points, the measured incident power density is greater than 0.01 of general public exposure limit defined by Iran national standard. The measured incident power density is between 0.002 and 0.01 of the defined general public exposure limit in 37.27%, 17.14%, 40.00%, 7.1429% and 13.08% of the measurement points in 5 cities where the number is 0% in the 2 other cities. Moreover, the incident power density is between 0.001 and 0.002 of the general public exposure limit in 24.54%, 2.31%, 15.71%, 13.33%, 5.38%, 17.14% and 11.54% of the measurement points. Most of the measurement points, i.e. 29.10%, 97.69%, 66.46%, 32.00%, 94.62%, 75.72% and 70.00% in the considered cities have an incident power density between 0.0002 and 0.001 of the general public exposure limit. Furthermore, in 7.27%, 0.714% and 0.67% of the measurement points in 3 cities, the measured incident power density is between 0.0001 and 0.0002 while the number is 0% in the 4 others. Finally, the measured incident power density is less than 0.0001 of the general public exposure limit, in 0.91%, 7.33% and 4.62% of the measurement points in 3 cities and the number is 0% the 4 others. Figure 2 gives a better illustration of these results where R_i shows $\frac{S_{mes,i}}{S_{ref,i}}$.

VI. Conclusion

The cumulative data recorded through broadband incident power density measurements up to 18 GHz in the urban areas of 7 cities in Iran were investigated and compared with the permissible values presented in Iran national standard no. 856. According to the analysis, it was concluded that through this wide frequency range, the total electromagnetic exposure is extremely below those presented in the standard.

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