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ORIGINAL ARTICLE

Electromagnetic field exposure assessment in Europe radiofrequency fields (10 MHz–6 GHz)

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Average levels of exposure to radiofrequency (RF) electromagnetic fields (EMFs) of the general public in Europe are difficult to summarize, as exposure levels have been reported differently in those studies in which they have been measured, and a large proportion of reported measurements were very low, sometimes falling below detection limits of the equipment used. The goal of this paper is to present an overview of the scientific literature on RF EMF exposure in Europe and to characterize exposure within the European population. A comparative analysis of the results of spot or long-term RF EMF measurements in the EU indicated that mean electric field strengths were between 0.08 V/m and 1.8 V/m. The overwhelming majority of measured mean electric field strengths were <1 V/m. It is estimated that $<1\%$ were above 6 V/m and $<0.1\%$ were above 20 V/m. No exposure levels exceeding European Council recommendations were identified in these surveys. Most population exposures from signals of radio and television broadcast towers were observed to be weak because these transmitters are usually far away from exposed individuals and are spatially sparsely distributed. On the other hand, the contribution made to RF exposure from wireless telecommunications technology is continuously increasing and its contribution was above 60% of the total exposure. According to the European exposure assessment studies identified, three population exposure categories (intermittent variable partial body exposure, intermittent variable low-level whole-body (WB) exposure and continuous low-level WB exposure) were recognized by the authors as informative for possible future risk assessment.

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INTRODUCTION

Currently, the data most widely available on exposure of the general public to radiofrequency (RF) electromagnetic field (EMF) within the 10 MHz–6 GHz range relate to radio and television broadcasting, base stations for telecommunications and mobile phones, cordless (DECT) phones, RF identification tagging systems, and wireless communications applications, such as WiFi, wireless local area network (WLAN) and worldwide interoperability for microwave access (WiMax). The political interest in emissions from these devices, and their potential association with various health effects, continues to increase, and it is anticipated that more data on public exposure to EMF in the whole-frequency spectrum will become available over the next few years. The newest generation of mobile telecommunications networks—LTE (long-term evolution), which will coexist with the existing technologies occupying the microwave spectrum—represents another growing source of RF EMF that is expected to add to RF exposure in the near future.

High exposures—that is, field levels exceeding the protection limits recommended for the general public—are experienced in occupational settings, for example, among broadcast tower maintenance personnel, RF welders, and induction sealers. However, the number of exposed persons is small, as relatively few people are working in such occupations.[1] Sources used by the general public, for example, wireless communication, data transmission or cooking on induction hobs, generate comparably much lower energy fields at the position of the user. However, this may also depend on the behavior of the user, especially with regard to the distance to the source. Nevertheless, occupational exposure assessment is beyond the scope of this review. In this paper, we aimed to present research efforts that have been done so far in European countries on assessment of exposure of the general public to RF EMF of various frequencies and sources. We present our findings in terms of those sources of exposure that cause the majority of RF EMF exposure in the general population, in terms of the approaches used in EU countries to measure fields related to these sources and also in terms of the results of those measurement campaigns identified. For the purposes of this paper, we have limited ourselves to exposure assessment of the general population of the EU. Clearly, exposure conditions elsewhere in the world may differ, and so our conclusions may not be considered more universally applicable.

METHODS AND RESULTS

Exposure Assessment and Monitoring in the EU

Various efforts have been made to determine the exposure of the general public to RF EMFs of several frequencies in European countries. We found that different methods of exposure assessment have been used for RF EMF over the last three decades, including: (1) spot or long-term EMF measurements; (2) personal exposimetry (PEM), and (3) characterization of exposure to RF EMF based on activities and sources. These activities are summarized in Table 1 and Figure 1, both by type and the frequency range

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addressed. At the European level, the first general review of the exposure assessment activities was issued by the EIS-EMF Project (European Information System on Electromagnetic Fields Exposure and Health Impacts) conducted by Joint Research Centre on behalf of DG SANCO.[2] Three primary criteria were applied in selecting studies looking at RF exposure assessment for inclusion in this study, as follows: (1) the data on RF EMF exposure range (10 MHz–6 GHz); (2) data had to be published in peer-review journal; and (3) measurements related to spot or long-term EMF measurement surveys, PEM or characterization of exposure to RF EMF based on activities and/or sources.

Spot or Long-Term EMF Measurements

On-site RF exposure measurement campaigns have been carried out in some European countries since the mid-1990s. These on-site (spot and long term) RF measurement campaigns were performed either as part of the planning permission process or upon request by the public or local authorities.

Narrowband and broadband measurement methods of assessing exposure levels to RF fields have been applied in the range from several MHz to 10 GHz. Most of them were focused on exposure in the frequency range of mobile telecommunications (base stations).

Large-scale measurement campaigns (audits/spot measurements) were carried and long-term RF monitoring systems have been installed in several EU member states, such as Austria,[3,4] Germany,[5] Italy,[6] Spain,[7] Belgium,[8,9] the Netherlands,[9] Sweden,[9] Greece[10] and United Kingdom.[11] Monitoring systems have been established as tools that attempt to manage public concerns about potential health effects of EMFs. However, their effectiveness has not yet been independently evaluated.

A cross-sectional study[3] in urban and rural areas near to base stations in Austria has shown that total RF EMF exposure, including mobile telecommunication signals, was far below recommended levels (maximum 1.24 V/m). The mean value of electric field strength was slightly higher in a rural area (0.13 V/m) than in an urban area (0.08 V/m). This discrepancy is because of the fact that only those households were selected that were close to mobile phone base stations, and base stations in rural areas typically transmit higher power as they are required to transmit over larger distances.

In another study,[4] spot measurements were taken in 226 households throughout Lower Austria. The overall RF EMF electric field had an arithmetic mean of 0.39 V/m; 15% was due to indoor sources and 85% was attributed to outdoor sources. The highest values of RF EMFs were caused by DECT telephone base stations (maximum 3.3 V/m) and mobile phone base stations (maximum 0.42 V/m). In Germany, locations nearby the base stations and publicly accessible places (i.e., hospitals or schools) were investigated. The maximum and minimum measured RF electric field strengths were 3.88 V/m and 0.03 V/m, respectively. The mean values were 1.42 V/m and 1.31 V/m when ignoring outliers.[5] In Italy, a national EMF-monitoring network has been established.[6] According to a summary of these measurements, 68.8% of recorded electric field strengths were <1 V/m, 22.6% were between 1 V/m and 3 V/m, 6.3% were between 3 V/m and 6 V/m, 2.2% were from 6 V/m to 20 V/m, and <0.1% were >20 V/m. In Spain, on-site measurements in the frequency range between 0.5 MHz and 2200 MHz were performed at 18 outdoor locations, and the median of electric field strength was 0.17 V/m. The frequency bands that contributed most to these levels were the three dealing with mobile telephony (34.8%); FM and TV contributed to a lesser extent with 6.5% and 0.9%, respectively.[7]

Table 1. RF EMF public exposure assessments in 20 European countries out of 27 member states.[a]

Country	*Sport and long-term measurements*	*Characterization of exposure (source, activity)*	*Personal exposimetry*
Austria	✓	✓	✓
Belgium	✓	✓	✓
Bulgaria	✓	—	—
Croatia	✓	—	—
Cyprus	✓	—	—
Denmark	✓	✓	—
France	✓	✓	✓
Germany	✓	✓	✓
Greece	✓	✓	—
Hungary	✓	—	✓
Ireland	✓	—	—
Italy	✓	✓	✓
Malta	—	✓	—
Netherlands	✓	✓	✓
Portugal	✓	—	—
Slovenia	✓	—	✓
Spain	✓	—	—
Sweden	✓	✓	—
Switzerland	✓	—	✓
UK	✓	✓	✓

[a]There are several member states for which we could not identify any measurements.

More recently, *in situ* exposure to RF base stations serving emerging wireless technologies was assessed at 311 locations, 68 indoor and 243 outdoor, in Belgium, the Netherlands, and Sweden.[8] The highest total electric field value (3.9 V/m) was measured in a residential environment. The highest median exposures were measured in urban environments (0.74 V/m), followed by offices (0.51 V/m), industrial (0.49 V/m), suburban (0.46 V/m), residential (0.40 V/m), and rural (0.09 V/m) environments. The average contribution made to the total electric field by GSM is >60%. With the exception of the rural environment, UMTS contributes on average >3%. Contributions of the emerging technologies LTE and WiMAX are on average <1%. Another paper characterized[9] *in situ* exposure from different RF sources and proposed a method for extrapolating in order to estimate worst-case LTE exposure. The median LTE exposures were 0.2 V/m and maximum LTE exposure was 0.5 V/m. Authors reported that the contribution of LTE to total exposure was limited to 0.4% on average.

In Greece, nationwide monitoring networks measuring the RF spectrum were used to collect the electric field strength at 46 different sites.[10] An overall assessment of the data showed that the mean electric field was 1.64 V/m. The authors reported that this rather high value can be explained by the fact that the remote measurement stations were installed at sites near the base stations. Exposures of the general public to radio waves at locations near 20 randomly selected GSM microcell and picocell base stations in the United Kingdom have been assessed.[11] The electric fields of the broadcast carriers transmitted by the base stations have been measured and scaled to include all other possible carriers. The assessment of the data showed that the electric field level was in the range of 0.003–1.8 V/m (values in the range 0.002–2% of the ICNIRP general public reference level). The highest exposure near any of the base stations was 8.6% of the ICNIRP reference level. Exposures close to microcell base stations were found to be generally greater than those close to macrocell base stations.

Other sources of general public exposure are broadcast towers for TV and radio that have a large coverage area and therefore operate at relatively high power levels up to ~1 MW. Although these transmitters could generate fairly high fields at ground level, most are not located in heavily populated areas and do not lead to high exposure of the population.[12] In the past, amplitude-modulated radio broadcasting was a major source of exposure, because of very powerful antennas operating to serve relatively large areas, so exposures >1 V/m were measured several kilometers away from the towers. General public exposure to AM radio transmitter was intensively investigated around the Schwarzenburg broadcast transmitter in Switzerland.[13,14] Exposure levels for AM radio transmitter in the range from 0.2 mA/m (0.015 V/m) to 6.7 mA/m (2.5 V/m) were measured with a mean value of 1.5 mA/m (0.56 V/m).

In the EU, analog broadcast systems have been—or are about to be—replaced by terrestrial digital video (DVB-T) and audio broadcast (DAB). In Germany, extensive on-site measurements were performed to determine public exposure to broadcasting transmitters. At the point with the highest exposure, measurements reached only 0.3% of the ICNIRP reference levels for general public. Schubert *et al.*[15] made measurements at more than 300 locations in a intervention study, looking at exposure "before" and "after" switchover from analog to digital. Statistical analysis of these measurement showed an increase in mean DVB-T exposure, which was mainly based on the increase in the radiated power at the transmitter stations. The maximal exposure value for analog TV in the "before" measurement was 0.58 V/m and 1.52 V/m in the "after" measurement for DVB-T. A comparison of analog FM radio and DAB showed that exposure to FM was higher by more than a factor of 10. However, planned increase of DAB transmitter power to improve DAB indoor coverage will reduce this difference.[15] A recent paper[16] reported a comparative analysis of data from surveys of mobile phone base stations in more than 20 countries across five continents.

Figure 1. Electromagnetic field (EMF) public exposure assessments in the European countries corresponding to the following exposure methods: (i) spot and long-term RF radiation monitoring systems, (ii) personal exposimetry, and (iii) characterization of exposure to RF EMF based on activities and sources (source of EU map: http://www.nationsonline.org).

The analysis was based on more than 173,000 measurement results and covered the period from 2000 onward. The study shows that the global mean value was only 0.52 V/m, which is almost 5500 times below the international guidelines.

Personal Exposimetry

Data collected from spot measurements in outdoor and indoor environments do not provide good insight into the exposure levels of individuals who are often exposed to multiple sources at the same time and move from one place to another. Data on the EMF exposure of individuals can only be obtained by explicit measurements, using, for example, PEMs, designing of which is a very challenging task. The uncertainty analysis when using a PEM is crucial and should follow next issues as follows: (1) body shielding; (2) residual uncertainties due to calibration; (3) measurement errors due to true RMS response; (4) how well the shaped frequency response of probes follows sensitivity variation with frequency; and (5) measurement artefacts (out-of-band pick-up/especially for the H-field probe; multi-signal error; and static pick-up). In addition, these measurements with PEM tend to underestimate or overestimate the actual RF EMF exposure.[17,18] A potential solution would be to determine correction factors based on the calibrations in order to modify the measurement results.[19]

A comparison was performed among the results of RF measurement campaigns in different urban areas across Europe using PEMs.[20] The considered campaigns were carried out in Belgium,[21] Switzerland,[22,23] Slovenia,[24,25] Hungary[26] and the Netherlands.[27] In some of these studies, measurements were performed in different microenvironments, such as offices or outdoor urban areas, to characterize typical exposure levels in these places (microenvironmental studies). The other studies were population surveys in which the personal exposure distribution in the population of interest was determined. The strategies for the recruitment of the study participants as well as the data analysis methods differed between these studies and therefore a direct comparison of their results is difficult. The exposure in all countries was found to be of the same order of magnitude. All studies concluded that mobile telecommunication is the largest source of exposure. In all countries, the mean exposure levels were found well below the ICNIRP exposure guidelines, with the highest exposure levels measured in transport vehicles (trains, car, and buses). In a more recent study, Joseph *et al.*[28] used mean personal field exposure levels (excluding mobile phone exposure) from five countries to calculate whole-body (WB) SAR values in models of a 1-year-old child and an adult male using a statistical multipath exposure method. All mean absorptions (maximal total absorption of 3.4 μW/kg for the child and 1.8 μW/kg for the adult) were well below 0.08 W/kg for the general public. Generally, incident field exposure levels were well correlated with WB absorptions (SAR_{wb}), although the type of microenvironment, the frequency of the signals, and the dimensions of the considered phantom modify the relationship between these exposure measures. With respect to exposures to the head, localized energy absorption resulting from an operating mobile phone is considerably higher compared with typical everyday energy absorption from a base station. Regarding WB exposure, however, the situation is not yet as conclusive. According to a rough dosimetric estimation, 24-h exposure from a base station (1–2 V/m) corresponds to $\sim$30 min of mobile phone use.[29]

The applicability of the RF personal measurements in several other studies has been demonstrated on different population samples in France,[30,31] the Netherlands,[32] United Kingdom,[33] and Germany.[34,35] In France, the results of a campaign[30,31] based on measurements made with PEMs demonstrated that in the downlink frequency range (GSM 900 MHz), $\sim$50% of the measurement samples were below the limit of detection (0.05 V/m). The same results were found in the GSM 1800 MHz band and in 3G systems, with 60% and 80% of measurements below the limit of detection, respectively. The total field mean value was 0.20 V/m, higher in urban areas, during daytime, among adults, and when moving. In the Netherlands, mean exposure to electric field over 24 h, excluding own mobile phone use, was 0.26 V/m.[32] Daytime exposures were similar, whereas nighttime exposures were about half the magnitude, and evening exposures were approximately double. The main contribution to environmental exposure (calling by participant not included) was from calling with mobile phones (37.5%), from cordless DECT phones and their docking stations (31.7%), and from the base stations (12.7%). The mean total exposure largely depends on phone calls of a high-exposure level and short duration. A cumulative distribution analysis of another measurement campaign in the United Kingdom[33] reported a mean exposure level of 0.11 V/m.

A residential RF exposure assessment was performed by Breckenkamp et al.[34] using PEMs to measure the electric field in fixed positions in bedrooms in 1348 households in Germany. The measurements were performed in 12 frequency bands from 88 MHz to 2.50 GHz. They found that DECT and WiFi account for ~82% of total exposure level and are the most important single-exposure sources. However, mean levels of exposure to these sources were 0.09 V/m. Exposure from mobile phone base stations adds only 6.3% to total exposure with a mean exposure level of 0.03 V/m. Another personal measurement campaign was carried out in Germany,[35,36] involving 3022 children and adolescents. Exposure to GSM 900 and GSM 1800 uplink and downlink, DECT phones, and WLAN were taken into consideration in the measurements. A 24-h RF exposure profile was generated using a personal dosimeter. The majority of measured exposure values were below the detection limit (0.05 V/m, 82% of the values during waking hours). The overall exposure to RF EMF in the considered frequency ranges was very low and ranged from a mean of 0.13% (all measurement values below the detection limit) to a mean of 0.92% of the ICNIRP reference level. Another publication[37] reported on the level of exposure to RF EMF in several cities in Germany and the association between the exposure to mobile phone frequencies and the well-being of adults. Exposure levels were on average <1% of the ICNIRP reference level. The findings indicate very low-exposure levels. The maximum exposure was 0.58% of the ICNIRP reference level, which is in agreement with some studies[38] using stationary measurements. In addition, as in previous studies, exposure levels were highest in the largest city. However, these measurements cannot be compared with stationary measurements, and the absolute values should be treated with caution.

Exposure Characterization of EMF-Emitting Devices

The exposure assessment of RF sources close to the human body needs dosimetric evaluation because of the complex RF EMF pattern nearby the RF devices. The most important device producing the highest exposure to RF of the public are mobile phones. Other portable RF wireless devices that also can be close to the body expose the individual at levels many times lower than a mobile. The averaged local exposure in the head induced by the mobile phone is considerably higher than that of the far-field sources, such as base stations and broadcasts sources. Although the EU limit of permissible SAR in the head is 2 W/kg, the real-life exposure to RF fields from mobile devices is less than the results of compliance tests. According to a Swiss study,[39] compliance tests of more than 600 mobile phones frequently used in the European countries produced between 2000 and 2005, and at maximum-radiated RF power provided a Gaussian distribution with around 1 W/kg peak SAR measured according to EN standards in a liquid head phantom.

According to the exposure assessment of epidemiological studies and information obtained from mobile telephone operators, phones operating in GSM mode work up to 30% of time at maximum power, whereas in 3G mode they only work at this level for 1% of the time. The largest exposure assessment study among the mobile phone users worldwide was performed within the INTERPHONE case-control epidemiological study.[40–42] In the INTERPHONE validation study, data on exposure duration of mobile phone use (duration of call) suggest that the average duration of call in Europe is ~500 min/month (~16 min/day). In general term, the brain exposure induced by a phone is ~0.5 W/kg for GSM and ~0.01 W/kg for UMTS. For base station with 0.1 V/m, the brain exposure induced by a phone is $\sim 10^{-6}$ W/kg.[43]

The field strength and distribution of SAR within the head are dependent among other things on the phone design and the communication system. The influence of the hand was mainly present for the UMTS communication system, as in GSM, the average output power is dominated by peak power excursion during handovers.[43] It is important to emphasize that at a distance of 10 cm from the mobile phone, the absorbed power in the head was 10 times lower than when assessed close to the ear. At 40 cm in front of the head, the maximum SAR over 10 g is close to 1% of the SAR obtained when touching the phone to head.

The normal operation for short range wireless devices and cellular phones fundamentally differ. Usually, exposure from DECT handsets, Bluetooth, WLAN, and WiFi devices is generally smaller than from cellular phones, but present for longer exposure periods. Older types of DECT docking stations continuously transmit EMF, however; therefore time-weighted average exposures at home from these sources are higher than from cell phones. Other studies on the exposure and dosimetry of short range wireless devices, body worn devices and base station wireless data communication devices in home and office environments[44,45] demonstrated that under typical conditions spatially averaged and 6-min time-averaged exposures of persons in RF fields of these applications are below ~0.1% of the ICNIRP reference level. Spatial and temporal peak values, however, may be considerably higher (2–3 orders of magnitude) than spatially averaged and 6-min time-averaged exposures. In the case of some transmitting devices operated in close proximity to the body (e.g., WLAN transmitters), local exposure can reach the same order of magnitude as the basic restriction; however, none of the devices considered in this study exceeded the limits according to the ICNIRP guidelines.

In the United Kingdom, power densities were measured at various spots both in homes and in school classrooms[46] close to WLAN 802.11b facilities. The results displayed a large range of electric field strength, from 0.02 V/m to 2.92 V/m. They concluded that the exposure of WLAN reduces rapidly with distance from the source, and that at a distance of ~1 m from the WLAN-Card the emission ranges from 2.37 V/m to 2.74 V/m. Peyman et al.[47] carried out experimental measurements to assess WiFi exposure levels from typical laptops and access points used in UK schools, evaluating the RF power densities and total emitted powers. The maximum electric field values recorded at 0.5 m around laptops and access points were 2.89 V/m and 5.72 V/m, respectively. The electric field reduced rapidly with distance for all tested WiFi devices (maximum electric field strength at 0.5 m of 2.87 V/m and 5.72 V/m, for laptops and access points, respectively; and at 1 m, 1.22 V/m and 2.60 V/m, respectively). Measurements performed both indoor and outdoor in Austria[45] have shown that the maximum electric field strength from WLAN applications ranged between 0.04 V/m outdoors and 8.31 V/m at a distance of 20 cm from a wireless router indoors.

Exposure assessment from 3G femtocells in Greece was investigated by Boursianis et al.[48] A femtocell access point at 2127 MHz was installed in one office and one home. The received signal code power of the pilot channel and the transmitted power were measured. The maximum received signal code power was found to be approximately −50 dBm (0,01 μW), whereas the maximum transmitted power to be approximately −10 dBm (0,1 mW). The electric field strength of the constant part of the femtocell signal, in proximity of the femtocell access point, was found at 0.26 V/m and 0.34 V/m in the office and at home, respectively. Persson et al.[49] examined the distribution of the output power of mobile phones and other terminals connected to a 3G network in Sweden, in rural, suburban, urban, and dedicated indoor networks. The average terminal output power for 3G voice calls was <1 mW for any environment. For data applications, the average output power was ~6–8 dB higher than for voice calls. For rural areas, the output power was ~2 dB higher, on average, than in urban areas.

The EMF absorption from DECT handsets are rather low, that is, <0.1 W/kg. The maximum exposure of WLAN and highest power of Bluetooth device (class 1) can lead to levels similar to those of mobile phones, that is, in the range of 0.1–1 W/kg; on the other hand under normal operational circumstances, these devices are operated at lower output power. The Bluetooth mobile headset devices operate at higher frequency than GSM and 3G mobile phones, they produce very low-level SAR <0.005 W/kg. The Bluetooth USB dongle devices can produce higher SAR touching the body, but these devices are in general not operated sufficiently close to the body for this to occur.[50] The maximum exposure within a radius of 1–2 m of these transmitters corresponds to typical exposures inside apartments that are close to mobile phone base stations. It is also interesting to compare the exposure from short range wireless devices with exposure from sources typically far from the body. Typical values inside buildings at distances up to 100 m from GSM base station sites are in the range of 0.1–1 V/m. Consequently, the electric field exposure caused by wireless home and office devices is in the range of exposure from a base station operated in close vicinity to an office or an apartment (10–200 m). However, given the growing penetration of wireless devices in the home and office, it is increasingly necessary to measure the combined exposure from the whole set of such devices.[39,50] There are several studies on the RF exposure generated by different RF devices inducing localized SAR. The comparison of local exposure against WB exposure needs the exposure characterization of RF-emitting devices in order to evaluate the total exposure to RF of the general population. This overview of exposure characterization of devices, including the exposure levels under real situation of wireless services, is not complete, as the research on this topic is not completed and many studies are still going on. Looking at the current development of wireless technology, the exposure situations are continuously changing. The differences between local, partial, and WB exposures are smoothing; therefore, modeling has an important role in these studies.[51]

Table 2. Summary of the measurement data on the RF EMF exposure using on-site (spot or long term) campaigns in Europe in mean total electric field strength in V/m or average exposure in % of the ICNIRP level.

Country	*Mean total electric field strength (V/m)*	*Description*	*Reference*
Austria	0.39	Spot measurements in 226 households	Tomitsch *et al.*[4]
Austria	0.13 (rural) 0.08 (urban)	Sport measurements of 10 randomly selected base stations	Hutter *et al.*[38]
Switzerland	0.56	AM radio transmitter	Altpeter *et al.*[13]
Greece	1.64	46 monitoring stations, 4 million measurements	Gotsis *et al.*[10]
UK	0.1–1.8	20 randomly selected GSM microcell, and picocell	Cooper *et al.*[11]
Spain	0.6	18 outdoor locations	Rufo *et al.*[7]
Belgium, Netherlands, Sweden	0.74 (urban) 0.46 (suburban) 0.40 (residential) 0.09 (rural)	311 locations, 68 indoor and 243 outdoor, in three European countries	Joseph *et al.*[8]
20 countries	0.52 global average	173,000 measurement surveys of mobile phone base stations in more than 20 countries	Rowley and Joyner[16]
Italy	68.8% below 1 22.6% from 1 to 3 6.3% from 3 to 6 2.2% from 6 to 20 0.1% >20	Nationwide EMF long-term monitoring network	Troisi *et al.*[6]

Abbreviations: EMF, electromagnetic field; RF, radiofrequency.

DISCUSSION

The comparative analysis of the results of spot or long-term RF EMF measurements in the EU indicated that the mean electric field strength was between 0.08 V/m and 1.8 V/m (Table 2). The vast majority (more than 60%) of measured mean electric field strengths were <1 V/m. It is estimated that $<1\%$ were above 6 V/m and only $<0.1\%$ were above 20 V/m. No exposure data above the limit values recommended by EU have been recorded in these surveys. Most public exposures from signals of radio and television broadcast towers were weak because these transmitters are usually far away and sparsely distributed over the country. On the other hand, the contribution of the RF exposure from wireless telecommunication technology is continuously increasing and its contribution was $>65\%$ of the total exposure.

According to the PEM data in EU, the mean total electric field strength is generally between 0.10 V/m and 0.26 V/m (Table 3). The overall results of the personal exposure assessment indicate that the average exposure to RF EMF is less than levels measured using spot or long-term measurement methods. This could be because most of the times subjects are indoors, where mobile signals have lower value, whereas most *in situ* measurements are performed outdoors and close to emitters. Another cause may be that, in case of personal exposure meters, body shielding explains part of the underestimation.[19,32] Furthermore, measurements of exposure levels of individuals using exposimeters have only been carried out in a limited number of countries. The majority of studies concluded that mobile telecommunication (particularly the use of a mobile and DECT/cordless phones) can be considered as the main contributor to personal RF exposure.

A review of the existing literature has not allowed us to make any conclusions with regard to the distribution of exposure to RF signals from different RF sources in the general population in Europe. The average level of exposure to RF in Europe is difficult to assess, as exposure levels have been reported heterogeneously in the different studies, and a large proportion of measurements in most studies were below detection limits. Furthermore, many studies were conducted in environments suspected to have high-exposure levels, such as in urban areas, or in close proximity to antennas or other sources. This comparative analysis of the results of RF exposure surveys in the EU has a number of limitations. The existing measurements were conducted for a number of distinct reasons, and no uniform or comparable measurement protocol was applied. We should be cautious in comparing absolute values between the studies identified, as different measurement instruments were used (e.g., narrowband spectrum analyzers or broadband survey instruments, operating over various frequency ranges), and averaging protocols and criteria for selecting the measurement locations also differed. In general, all personal measurement campaigns in EU showed that a substantial proportion of RF EMF levels from different communication technologies are below the detection limit (0.05 V/m) of the current exposimeters when employed in the everyday environment. To account for this, Röösli *et al.*[52] suggested that summary statistics of exposimeter data should be calculated by robust regression on order statistics (ROS) method that gives more reliable and informative results. ROS is a method that fits a normal distribution to the data above the detection limit (detected values). This produces reliable summary estimates of personal measurements with a substantive proportion of non-detects.

CONCLUSION AND RECOMMENDATIONS FOR FURTHER STUDIES

The exposure level in the living environment is continuously increasing. According to the results of the first measurement campaign[53] in several cities in the United States of America, the average exposure level in urban areas in 1980 was ~ 0.14 V/m. In 1998, similar survey was elaborated in Sweden,[54] where the RF exposure level in the urban area was 0.43 V/m. Another result from the survey measurements in dense populated areas in Greece[10] showed exposure levels of 1.21 V/m in dense urban areas and 0.7 V/m in rural areas. For instance, in Austria from 2006 to 2009, the 5% trimmed arithmetic mean exposure to UMTS increased by a factor of 13.8 and for wireless internet by a factor 9.9.[55] Although the older studies[52,53] showed that the principal sources of RF EMF were from signals in the broadcast bands, some recent studies in EU showed that almost 65% of the RF exposure radiated by the wireless telecommunication devices. This trend seems to be continuously increasing. The major part of the RF public exposure comes from mobile and wireless portable devices, and not from the fixed transmitters.

In general, the RF exposure levels of the general public that come from the fixed RF sources, including LF/MF broadcast, VHF broadcast, UHF TV, and telecommunication systems, were very low with respect to the limit values recommended by EU.[56] The overall results for EU show that >60% of measured total RF EMF field strength was <1 V/m, <1% was >6 V/m, and <0.1% was above 20 V/m of equivalent electric field strength. The cumulative dose may also be affected by the radiation effectiveness of the phone, network coverage, and environmental and user factors. The available research data demonstrated that the indoor RF exposure is increasing faster than outdoor exposure because of the wide spreading of home wireless devices and short range communication systems. The dominant source with respect to local and cumulative exposure is, however, the mobile phone. Looking at the geographical distributions, no noticeable differences can be found between the EU countries (or they are difficult to distinguish). However, the exposure levels and contribution of different sources showed differences in rural and urban areas.

Table 3. Summary of the measurement data on the RF EMF exposure of individuals using PEM in Europe in mean total electric field strength in V/m or average exposure in % of the ICNIRP level.

Country	*Mean total electric field strenght (V/m)*	*Authors*
Belgium	0.12	Joseph *et al.*[21]
Switzerland	0.24	Frey *et al.*[22,23]
Slovenia	0.27	Trček *et al.*[24]
Hungary	0.10	Thuróczy *et al.*[26]
Netherlands	0.15	Bolte *et al.*[27]
France	0.21	Viel *et al.*[31]
UK	0.11	Mann[33]
Germany[a]	0.09	Breckenkamp *et al.*[34]
Netherlands	0.26	Bolte and Eikelboom[32]

Abbreviations: EMF, electromagnetic field; PEM, personal exposimeters; RF, radiofrequency
[a]Additional German studies on the average exposure in % of ICNIRP reference level: 0.92 (Heinrich *et al*)[35] and 1.00 (Thomas *et al*)[36] in percent of ICNIRP reference level, respectively.

In the evaluation of human exposure to EMF, several possible classifications and clusters of exposure have been recognized as follows: indoor *vs* outdoor, long term *vs* acute, and exposure by sources far from the human body (so-called "far-field" exposure) *vs* sources close to the human body (so-called "near-field" exposure). Classification according to perception of the exposure, such as voluntary *vs* involuntary, is also used, but this categorization does not have any scientific basis or real value in exposure assessment. For example, as emission and propagation of electromagnetic waves of base stations are influenced by technical and environmental parameters, there are strong limitations in the computational assessment of exposure around mobile phone base stations. According to the study conducted by Neitzke *et al*,[57] the results of the measurements confirm the hypothesis that it is impossible to find a simple indicator for the assessment of exposure because of mobile phone base stations in epidemiological studies.

Regarding the possible future risk analysis in order to evaluate the strength of evidence for adverse effects arising as a consequence of exposure to EMF, three main RF public exposure categories could be classified. These categories in the RF range include: (1) intermittent variable partial body exposure; (2) intermittent variable low-level WB exposure; and (3) continuous low-level WB exposure (Table 4).

From the great body of exposure assessment data from EU countries, we could conclude that nobody in the studied populations was exposed above limit values recommended by EU. Owing to this fact, there is no convincing scientific evidence that the very low environmental levels of RF fields, generally, orders of magnitude below any of the scientifically based exposure limits, result in adverse health effects. Although RF exposure surveys have been carried out in the general environment using recently developed personal exposure meters, comprehensive measurement of exposure with a true population-based sampling frame and a common protocol across countries has never been conducted. This has limited the generalizability of survey results and hampered attempts to estimate population level exposures. Personal surveys have also focused on far-field sources where only a selected number of

Table 4. Classification of RF public exposure regarding the possible future risk analysis.

Exposure classification	*Description, main sources and relevance of risk evaluation*
Intermittent variable partial body exposure	Highest level of exposure category, including mostly the mobile and wireless handsets (body-close portable devices). The exposure levels are highly variable and local. The exposure is intermittent. The levels of exposure are below the recommended European exposure limit (2 W/kg), but the local maximum may be close to the limit. The most characterstic exposure unit is the SAR (W/kg). Typical sources include: mobile handsets (GSM, 3G), DECT phones, and other wireless handsets. This category is the most important for some risk evaluation studies.
Intermittent variable low-level whole-body exposure	Medium level of exposure category, including mostly the indoor wireless portable and fixed devices. The exposure levels are variable, inhomogeneous whole, and/or partial body. The exposure is intermittent, the mean and maximum exposure levels are well below the recommended European exposure limits. The most characteristic exposure units are the electric and magnetic field strength or under special conditions the SAR. Typical sources include: WiFi, WLAN, DECT base stations, wireless, and Bluetooth USB dongle devices, and other indoor wireless portable and surveillance devices. This category has limited importance for risk analysis, but under some conditions (i.e., children exposure from WiFi and baby surveillance systems) may be relevant for investigations.
Continuous low-level whole-body exposure	Low level of exposure category, including mostly the fixed outdoor sources of TV and radio broadcasts, and wireless telecommunication systems (mobile base stations and body far-fixed sources). The exposure levels are variable in space and time. The exposure is continuous, whole body and the mean and maximum exposure levels are many times below the recommended European exposure limits (typically <1 V/m). The most characteristic exposure units are the electric and magnetic field strength. Typical sources: TV and radio broadcasts antennas, mobile telephone base stations (GSM, 3G, LTE), WiMAX base stations. This category has been studied previously for risk analysis; therefore, it has limited importance for risk analysis except the investigations of long-term changes of exposure to RF of general population.

Abbreviations: RF, radiofrequency; WiMAX, worldwide interoperability for microwave access; WLAN, wireless local area network.

broadband frequency bands have been investigated. A novel development of PEMs should be motivated to assess cumulative exposure from other RF sources, including AM radio and other emerging technologies (i.e., LTE and UWB).

In addition, future project should focus on providing the mapping of EMF exposure level on national level that will be performed by frequency selective PEMs in parallel computing the reduction of EMF exposure by 3D propagation modeling. Extending this work to other countries in Europe to provide spatial estimates of RF field strength for use in both epidemiological investigations and health impact assessment is needed. Further, as available exposimeters are offering insight into time-weighted average exposure, other specific exposure response models should be investigated (i.e., modulation of the signal and number of peaks above a threshold). Finally, although the exposure of general public in intermediate frequency range (frequency between 300 Hz and 10 MHz) is increasing, little information on exposure is currently available. Systematic spot measurements are needed to enhance knowledge about IF exposure distribution.

As final comments, although all EMF exposure assessments, surveys of sources, and epidemiological studies in EU countries have so far suggested that everyday exposure levels of the general public are well below the current guidelines, it remains a challenge to predict whether groups in the population with elevated exposure exist and, if so, to what extent they are exposed above the normal ''background'' level. Technologies are also changing rapidly and the impact of this on total exposure of an individual remains unclear.

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