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Radiofrequency exposure of people living near mobile-phone base stations in France

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ABSTRACT

In response to the demand from a growing number of people concerned about the possible impact of RF-EMF on health, the French National Frequency Agency (ANFR) has published a standardized protocol for in-situ measurements of radiofrequency electromagnetic fields (RF-EMF). This protocol was based on the search for the point of highest field strength and the use of spot measurement.

In the framework of an epidemiological study, such spot measurements were implemented in the homes of 354 participants located in urban areas within 250 m of a mobile-phone base station (MPBS) and in the main beam direction of the antenna. Among the participants, more than half accepted to be enrolled in a longer-term study, among whom 152 were equipped with a personal exposure meter (PEM) for 48 h and 40 for seven continuous days. Both spot and PEM measurements quantified downlink field strengths, i.e. FM, TV3-4-5, TETRA I-II-III, 2 GHz–5GHz Wi-Fi, WiMax, GSM900, GSM1800, UMTS900, UMTS 2100, LTE800, LTE1800, and LTE2600.

Spot measurements showed a mean/median field strength of 0.58/0.44 V/m for total RF-EMF and 0.43/0.27 V/m from the MPBS. RF-EMF from the MPBS was the dominant source of exposure in 64% of households. Exposure to RF-EMF was influenced by the position of the windows with respect to the MPBS, in particular line-of-site visibility, the distance of the antenna and the floor of the apartment. The PEM surveys showed the measured exposure to be higher during outings than at home and during the day than at night, but there was no difference between the weekends and working days. There was a strong correlation between exposure quantified by both spot and PEM measurements, although spot measures were approximately three times higher than those by PEMs.

This study is the first to assess exposure to RF-EMF of people living near a MPBS in urban areas in France. These preliminary results suggest the value of using spot measurements to estimate the impact of the evolution of the mobile-phone network and technology on the exposure of populations to RF-EMF. The low levels of RF-RMF expressed as mean values do not necessarily rule out possible health effects of this exposure.

1. Introduction

The very rapid development of communication technology experienced over the last two decades has resulted in the proliferation of mobile-phone base stations (MPBS), often visible at the top of buildings along many streets in urban areas. This phenomenon has likely given rise to new concerns among the urban population about the effects of exposure to radiofrequency electromagnetic fields (RF-EMF) on health. Associations have thus been created in France to gather population complaints and discuss this topic with relevant authorities. As generally reported, involuntary exposure to base stations appears to be of higher concern than direct exposure to the voluntary use of mobile phones, which is not permanent, but much higher in terms of received energy.

In France, measurement campaigns have been undertaken by the

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National Frequency Agency (ANFR) to mainly estimate indoor exposure of populations to RF-EMF in many parts of the country, using a standardized protocol (ANFR, 2017). The measurements are made by accredited laboratories and the results are published and displayed on the “Cartoradio” website (Cartoradio, 2018). The ANFR can also order measurements in specific households upon demand of the occupants.

The assessment of exposure to RF-EMF for epidemiological studies is based on five main approaches: (i) basic exposure indicators: for example, base station density, distance from a base-station, and functional status (operation/no-operation) of a proximal base station, (ii) the use of more advanced geospatial propagation models (Frei et al., 2010); (iii) spot measurements, usually indoor, conducted using sophisticated devices (broadband and/or spectrum analyzer), as in the French ANFR protocol (Berg-Beckdhoff et al., 2009; Hutter et al., 2006; Tomitsch and Dechant, 2015); (iv) approaches based on personal measurements made by trained personnel, within an indoor or outdoor microenvironment (city centers, workplaces, airports, etc.), according to a standardized protocol (Sagar et al., 2018a); and (v) personal measurements made from 1 to 7 days by volunteers supplied with light personal exposure meters (PEMs) and moving freely according to their usual activities (mobile monitoring). These volunteers are generally requested to note their location, activities, and trips in a diary log (Röösli et al., 2008; Heinrich et al., 2010).

Standardized spot measurements with sophisticated devices, such as spectral analyzers, enable reliable determination of specific exposure to many sources and the contribution of each to total RF-EMF exposure. However, these estimations do not reflect the true exposure of active individuals, who generally move from place to place during both workdays and weekends. Although the use of PEMs has been recommended in epidemiological studies to measure exposure from environmental far-field RF-EMF sources in everyday life (Röösli et al., 2010), their use is limited due to the high cost and large effort required by study participants. Furthermore, it is still unclear to what extent PEM readings are affected when personal mobile and cordless phones are used, and the extent to which PEM measurements are affected by RF-EMF close to the body is unknown.

A cross-sectional study was conducted in five large cities in France to investigate the relationship between exposure to RF-EMF from MPBSs and self-reported non-specific symptoms and sleep disorders. The exposure of each participant was characterized using not only spot measurements in participants’ homes but also personal measurements using PEMs. Both techniques enable investigation of the exposure to RF-EMF of different frequency bands. Here, we summarize the comprehensive RF-EMF exposure data collected from the 354 participants in the epidemiological study. The objective was to: (i) assess total exposure to RF-EMF inside homes located near a MPBS and the contribution of base stations to total exposure; (ii) better identify housing features that may influence exposure to RF-EMF from MPBSs and; (iii) compare the estimated exposure from indoor spot measurements and that based on stationary devices and PEM measurements.

2. Materials and methods

2.1. Participants and study design

The study population included adults (18 years of age and older) living in five large cities of metropolitan France: Paris, Antony (suburb of Paris), Lyon, Lille, and Angers. They were selected according to the following protocol. Within each urban area, MPBSs were selected if they had been operating for more than two years, not strongly contested by local residents at the time of their installation, not in close proximity to other major radio emission sites, rich in mobile communication services (GSM900, GSM1800, UMTS900, UMTS2100, LTE800, LTE1800, LTE2600) and, if possible, multi-operator (BOUYGUES, SFR, ORANGE, FREE). Then, buildings located 250 m or less from a MPBS and in the main transmitted beam direction of the antennas (with at least one residential unit potentially exposed) were identified. The study population corresponded to the households within these buildings for which the fixed-line phone number was available in the French telephone directory. A letter from the French Agency for Food, Environmental, and Occupational Health & Safety (ANSES) was sent to all the identified households to present the study entitled "Study on the Links between Health and the Urban Environment". This letter informed them that they would receive a call from a survey institute to complete a questionnaire (duration: 15–20 min) and schedule an appointment to carry out spot measurements at their home (without specifying their nature). The telephone survey was held between late 2015 and mid-2017, depending on the city. At the end of the interview, a time slot for home spot measurements was decided in consultation with the interviewee.

At the end of the spot measurement procedure, which took approximatively 1 h, each participant was asked whether he/she was interested in being a volunteer for a 2-day or 7-day PEM measurement study. In the case of a positive response, a new time slot was determined to launch the long-term study with a PEM.

Once the participant was supplied with a PEM, he/she was given a space-time diary to report the places where he/she was successively located during the survey. Four categories were proposed: home, trips, workplace, and other places. The diary was divided into 5-min periods.

2.2. RF-EMF exposure assessment

2.2.1. Spot measurement according to the protocol of ANFR

The ANFR DR15-4 protocol (ANFR, 2017) to assess public exposure to RF-EMF consists of two successive steps of spot measurements, called “Cas A” and “Cas B”. “Cas A″ is a rapid and comprehensive broadband field strength measurement over a frequency range [100 kHz - 6 GHz] performed in five locations selected by the operator as the supposedly most-exposed areas of the flat and in the rooms where the study participant spends the most time (bedroom, living room, kitchen). The measurements are made 1.5 m above the ground. “Cas A″ measurements produce a rapid and accurate map of the electric field distribution in the home. Measurements are performed with a broadband field meter (from WAVE CONTROL), composed of an SMP2 base unit and a WP6 measurement probe. This equipment allows a root mean square measurement of the electric field intensity with a sensitivity of 0.2 V/m “Cas B″ consists of a selective spectrum analyzer measurement performed at a single point (that with the highest exposure among the five broadband field strength measurement points in “Cas A″) at three heights, i.e.: 1.10, 1.50, and 1.70 m, the values being averaged. “Cas B″ is measured at a specific time (and is not an extrapolated value). Spectral analysis of this single measurement allows determination of the contribution of each service (radio, television, mobile telephone, etc.) in the total field. The measurement is performed with a selective field analyzer (NARDA), composed of an SRM 3006 base unit and three measurement probes. This equipment provides an accurate measurement of each frequency in the 100 kHz – 6 GHz band. These frequencies are measured in the channel power mode for each type of service and a quadratic sum is calculated for each for all non-contiguous bands. This equipment allows a root mean square measurement of the electrical field intensity, with an average sensitivity of 0.001 V/m. During the measurement, all existing indoor sources (Wifi, DECT, etc.) were on and the operator noticed whether or not the base station antenna was visible from the home.

2.2.2. Long term, mobile measurements with personal exposure meters (PEMs)

The measurement over time was carried out using an exposure meter that delivers a value for each activated "service" according to the measurement time step defined during device configuration (55 s for "two days" of follow-up and 150 s for "seven days" of follow-up). The sampling time of the PEM determines its ability to detect the peaks in exposure and thus to optimally calculate the exposure metrics. Sampling intervals of 55 and 150 s were chosen for the 48-h and 7-day measurements, respectively, to provide sufficient autonomy to the PEM batteries. The PEMs were calibrated according to the manufacturer's recommendations: the measured values were automatically corrected by the calibration factors stored in the device.

Measurements were performed using an EME SPY 200 selective field PEM (SATIMO, France). The PEM measured the RF electric field strengths in 15 frequency bands used for communication and broadcasting (Table 1). These bands were measured in channel power mode. A quadratic sum was calculated for each service for all non-contiguous bands. This equipment can compute a root mean square measurement of the electrical field intensity with a sensitivity of 0.005 or 0.010 V/m, depending on the measured bands.

PEMs were worn in a shoulder bag. During the day, volunteers kept the bag on their shoulder when traveling, including moving from one room to another in their home. When they were sitting, and during invasive and/or aquatic physical activities, they could take off the bag and keep it close to them. During the night, volunteers put the shoulder bag on the bedside table. Under no circumstances were they to take the PEM out from the bag or handle it.

2.3. Statistical analysis

RF-EMF were divided into two categories according to the emitting sources (i) those emitted by MPBSs (i.e.: downlink LTE, GSM, and UMTS): and (ii) "other RF-EMF".

All exposure calculations are expressed in electrical field strength (V/m), which is relevant for far-field exposure. Exposure was metered as the quadratic mean of all measured values over the relevant measurement time period. The main exposure index is the mean value of the various sources of exposure for both categories of RF-EMF (i.e.: MPBSs and "other"). Another index used was the 95th percentile of these values calculated over the entire measurement time period (peak exposure value). The individual field values below the limit of determination (0.01 or 0.005 V/m, depending on the frequency band) were replaced by half of the limit (i.e., 0.005 or 0.0025 V/m) (9).

Differences in exposure due to location and features of the home were determined through spot measurements according to the official French protocol. Differences as a function of the time and activity were determined based on the PEM measurements made by volunteers. Spearman rank correlations (Rs) were estimated between the values obtained from both spot and PEM measurements (Frei et al., 2010). The association between exposure and visibility of the base station antennas was investigated using a non-parametric test (Kruskal-Wallis).

Statistical analyses were carried out using SAS version 9.4 and R version 3.3.2.

Table 1
Personal exposure meter frequency bands (EME SPY 200, SATIMO, France).

Band Name	Range (MHz)	Active source
FM	87–107	VHF broadcast radio
TV 3	174–223	Digital audio broadcasting
TETRA I	380–400	Terrestrial trunked radio
TETRA II	410–430	Terrestrial trunked radio
TETRA III	450–470	Terrestrial trunked radio
TV 4&5	470–770	UHF broadcast television
LTE[a] 800 (DL[b])	791–821	4G base stations (down link)
GSM[c] (DL[b])) + UMTS[d] 900 (DL[b])	925–960	2G/3G base stations
GSM[c] 1800 (DL[b])	1805–1880	2G base stations
DECT	1880–1900	Digital enhanced cordless telephony
UMTS[d] 2100 (DL[b])	2110–2170	3G base stations
WIFI 2G	2400–2483.5	Wireless networks and microwave ovens
LTE 2600 (DL[b])	2620–2690	4G base stations
WIMax	3300–3900	Wireless networks
WIFI 5G	5150–5850	Wireless networks

[a] Long-Term Evolution.
[b] Down Link: Received radio signal from the point of view of a mobile phone.
[c] Global System for Mobile Communications.
[d] Universal Mobile Telecommunication System.

3. Results

3.1. Home spot exposure measurements

In total, 354 people in the five sites were recruited for home spot measurements as required by the design of the epidemiological study. The characteristics of the dwellings are presented in Table 2. Most dwellings (95%) were apartments with double-glazed windows (95%). Almost a quarter (23%) were located on the sixth floor or higher, with the rest equally distributed among the lower floors (10–15% by floor). Most (73%) of the apartments were located between 50 and 200 m from a MPBS and less than half (43%) were facing the antenna.

The emissions from a MPBS were predominant in the RF-EMF exposure in more than 60% of the surveyed homes (225/354). Wi-Fi, RADAR, radio-diffusion, and HF emissions were each predominant for 6–12% of the homes and the other services for less than 2.5%.

The total exposure level by spot measurement varied from 0.05 V/m to 3.64 V/m, with a mean value of 0.58 ± 0.47 V/m and a median value of 0.44 V/m (Table 3). These values are far below those of the guidelines recommended by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) based on the heating of tissues (41 V/m for 900 MHz, 58 V/m for 1800 MHz, and 61 V/m for 2100 MHz). The range of exposure from MPBSs was quite similar to the total exposure levels (they varied from 0.03 to 3.58 V/m) but the mean and median values of exposure were 0.43 ± 0.48 V/m and 0.27 V/m, respectively. The 25th and 75th percentiles of the MPBS values were 0.124 and 0.520 V/m, respectively. Total measured exposure levels were below 2 V/m for 97% and below 0.5 V/m for approximately 60% of households. Considering the level of exposure associated with a MPBS, 98% of households were below 2 V/m and 73% below 0.5 V/m.

Among the housing features likely to influence RF-EMF exposure

Table 2
Housing characteristics.

Characteristic[a]	N = 354
Housing (%)	
detached house	1.1
adjacent house	3.7
apartment building	95.2
Glass type (%)	
simple	3.7
double	95.2
Both	1.1
Floor (%)	
Ground floor	12.8
1st	12.2
2nd	13.9
3rd	15.9
4th	10.8
5th	10.8
6th and above	23.6
Distance (%)	
< 10m	0.8
10 - 50m	16.8
50 -100m	38.6
100 - 200m	34.7
200 - 250m	9.1
Orientation (%)	
facing	43.4
other	56.6
Visibility of MPBS (%)	
Yes	33.1
No	66.9

[a] Missing values (% of total sample): housing 0.3%, type of glass in the windows 0.3%, floor 0.6%, distance 0.6%, orientation 1.1%, visibility 0.3%.

Table 3
Home spot exposure measurements (V/m).

	Minimum	Median	Mean	Standard deviation	Maximum
Total sources	0.16	0.44	0.58	0.47	3.64
MPBS	0.03	0.27	0.43	0.48	3.58
Other sources					
- High-frequency services (HF)	0.05	0.09	0.12	0.15	2.27
- PMR (Public Mobile Radio) (TETRA)	0.05	0.05	0.05	0.02	0.18
- FM Radio	0.02	0.05	0.10	0.14	1.24
- Beacons of PMR network	0.05	0.05	0.06	0.04	0.44
- Television (TV)	0.05	0.06	0.07	0.04	0.40
- Cordless telephone (DECT)	0.01	0.01	0.03	0.05	0.37
- Radar	0.00	0.09	0.10	0.06	1.06
- Wi-Fi (WiFi, WiMAX, WLAN)	0.00	0.06	0.11	0.13	1.01

levels (Table 4), the spatial orientation of the windows with respect to the MPBS appeared to be the most important: the mean value of exposure levels to total sources/MPBS was 0.73/0.62 V/m for households with windows facing the base station versus 0.46/0.29 V/m for the others. Measured exposure was higher in the upper floors (6th and above), but the increase was not linear. Comparison of the exposure levels (total and associated with MPBSs) measured in the five tested urban areas of France showed the median and mean exposure levels to be clearly lower in the smallest city (Angers) and higher in the largest city (Paris). Exposure measured in Lille, Lyon, and a Paris suburb showed intermediate values. Exposure decreased with increasing distance and was significantly higher ($p < 0.0001$) when the base station antenna was reported by the operator to be visible from home, with a visible/non-visible ratio above 2 for both the mean and median values.

Table 4
Home spot measurements according to urban area and building features (V/m).

		Total sources	MPBS sources
		Mean (sd)	Mean (sd)
Urban area	Angers	0.35 (0.16)	0.24 (0.19)
	Antony	0.69 (0.43)	0.37 (0.27)
	Lille	0.56 (0.44)	0.42 (0.46)
	Lyon	0.56 (0.40)	0.39 (0.42)
	Paris	0.69 (0.62)	0.59 (0.65)
Housing	multiapartment	0.59 (0.48)	0.44 (0.49)
	adjacent	0.35 (0.15)	0.23 (0.19)
	detached	0.39 (0.07)	0.29 (0.05)
Glass type	simple	0.45 (0.20)	0.31 (0.24)
	double	0.58 (0.48)	0.44 (0.49)
	both	0.33 (0.04)	0.08 (0.04)
Orientation	in front of	0.73 (0.60)	0.62 (0.62)
	others	0.46 (0.30)	0.29 (0.27)
Floor	ground floor	0.36 (0.27)	0.20 (0.28)
	1st	0.39 (0.26)	0.23 (0.26)
	2nd	0.43 (0.23)	0.28 (0.26)
	3rd	0.57 (0.46)	0.42 (0.42)
	4th	0.60 (0.43)	0.44 (0.46)
	5th »	0,59 (0,44)	0.42 (0.44)
	6th and above	0.86 (0.63)	0.75 (0.65)
Distance from antenna	<50 m	0.55 (0.46)	0.40 (0.48)
	50–100 m	0.51 (0.36)	0.37 (0.38)
	100–250 m	0.49 (0.40)	0.32 (0.33)
Visibility	yes	0.80 (0.61)	0.71 (0.64)
	no	0.47 (0.33)	0.29 (0.30)
Visibility and distance from antenna	Visible & < 50 m	0.80 (0.73)	0.69 (0.78)
	Visible & 50–100 m	0.73 (0.51)	0.59 (0.54)
	Visible & 100–250 m	0.59 (0.49)	0.51 (0.50)
	Not Visible & < 50 m	0.50 (0.38)	0.29 (0.31)
	Not Visible & 50–100 m	0.39 (0.16)	0.25 (0.18)
	Not Visible & 100–250 m	0.44 (0.25)	0.26 (0.19)

3.2. Mobile measurements with PEMs

All participants in this PEM survey were volunteers who had participated in the home spot measurements and were divided into two panels: (i) a panel of 152 volunteers accepting to wear the PEM for two days (48 h) and (ii) a panel of 40 volunteers accepting to wear the PEM for a week (seven consecutive days), among whom 10 had previously participated in the above-mentioned two-day survey.

Due to various problems encountered by the participants in operating the device, the mean duration of the measurements per participant was actually 1.8 days and 1.97 nights for the two-day survey and 6.7 days and 6.97 nights for the seven-day survey.

The proportion of measured values for MPBS emission below the determination limits (0.005 V/m) for both surveys was maximal for LTE 2600 (39% in the two-day and 32% in the seven-day survey), followed by the LTE 800 frequency band (17 and 21%). These two frequency bands were the most recently developed for mobile-phone services (4G). The lowest proportion was observed for GSM + UMTS 900 (16 and 20%).

The mean cumulative exposure was significantly higher for the day than night for both studies: 0.17 versus 0.14 V/m ($p < 0.0001$) for the two-day survey and 0.20 versus 0.17 V/m ($p < 0.003$) for the seven-day survey (Table 5). The day/night difference was also significant for P95 values of exposure ($p < 0.0001$) (data not shown). Furthermore, the mean exposure was slightly higher for the seven-day survey participants than for the two-day survey participants. The mean exposure of the vast majority of participants was below 0.2 V/m, but this threshold was more often exceeded during the day.

The mean and P95 values of exposure measured at various locations and during various activities of the survey participants (i.e., home, trips, workplace, and other places) are presented in Table 6. The mean and P95 values of exposure varied significantly depending on the location. For the two-day panel, the mean exposure was highest when measured during trips (0.21 V/m), followed by other places (0.17 V/m), and at home (0.16 V/m), whereas participants were much less exposed at the workplace (0.11 V/m). The P95 value was also higher during trips (0.17 V/m), but the value measured at home was very similar (0.16 V/m). The maxima of both the mean and P95 values were measured at home. The variations and differences between locations of the mean and P95 values were quite similar for the seven-day panel.

For both the two-day and seven-day panels, the difference between the mean and P95 values of exposure measured during workdays and the weekend was not significant (0.15/0.18 V/m for the two-day and 0.15/0.16 V/m for the seven-day survey, respectively).

3.3. Comparison between home spot and PEM measurements

A statistical non-parametric Kruskal-Wallis test showed a strong correlation between spot measurements and two-day and seven-day

Table 5
Cumulative MPBS exposure for 12 h.

MPBS (V/m)	Cumulative 12 h exposure	Number of days	Mean (sd)	min	median	max
Panel « two-day »	day (8 h–20 h)	274	0.17 (0.14)	0.01	0.14	0.97
	night (20 h–8h)	299	0.14 (0.15)	0.01	0.09	1.07
Panel « seven-day »	day (8 h–20 h)	268	0.20 (0.19)	0.01	0.15	1.18
	night (20 h–8h =	279	0.17 (0.19)	0.01	0.11	1.27

Table 6
MPBS exposure according to location (V/m).

	Panel « two-day »				Panel « seven-day »			
	Mean (sd)	Min	Median	Max	Mean (sd)	Min	Median	Max
MPBS exposure mean								
Location	($p < 0.0001$)				($p = 0.001$)			
Home	0.16 (0.16)	0.01	0.12	0.91	0.20 (0.21)	0.01	0.13	0.92
Journey	0.21 (0.12)	0.02	0.19	0.56	0.26 (0.12)	0.05	0.26	0.61
workplace	0.11 (0.10)	0.01	0.09	0.47	0.11 (0.08)	0.01	0.08	0.30
Other	0.17 (0.12)	0.02	0.14	0.81	0.20 (0.10)	0.06	0.19	0.44
P95 of MPBS exposure								
Location	($p = 0.0007$)				($p = 0.01$)			
Home	0.16 (0.18)	0.01	0.1	1.07	0.21 (0.23)	0.01	0.13	1.02
Journey	0.17 (0.11)	0.02	0.16	0.59	0.22 (0.14)	0.03	0.19	0.69
workplace	0.1 (0.12)	0.01	0.06	0.6	0.09 (0.10)	0.01	0.06	0.34
Other	0.14 (0.14)	0.01	0.09	0.91	0.18 (0.14)	0.01	0.15	0.54

PEM measurements, with calculated Spearman correlation coefficients of 0.68 ($p < 0.0001$) and 0.86 ($p < 0.0001$), respectively (Fig. 1). However, the mean value of spot measurements was clearly higher than the mean value of personal measurements made at home (ratio spot/PEM = 2.9 for both the two-day and seven-day surveys).

4. Discussion

This study is the first to assess exposure to electromagnetic fields of people living near a MPBS in urban areas in France. The main specificity of the study was to compare the levels of exposure to RF-EMF measured at home using a sophisticated narrow-band device according to a standard method and those measured using PEMs for 48 h or one full week in everyday life. In a recent systematic literature review of RF-EMF exposure studies conducted in European countries, Sagar et al. (2018b) identified 21 papers published between January 1, 2000 and April 15, 2015, amongst which 10 were spot-measurements studies, five personal measurement studies with trained researchers, five personal measurement studies with volunteers, and only one a study combining data collected by volunteers and trained researchers (Frei et al., 2010). However, in this last study, spot measurements were only taken in the bedroom (average of seven measurements at the center and corners of the room), without seeking the most exposed point.

4.1. Study strengths and limitations

The use of two different types of measurements to quantify radiofrequency exposure enables the careful evaluation of the actual exposure of a resident close to a MPBS. The temporal variations in the field are quadratic in nature, as they are the sum of multiple contributions, especially in urban areas. The increase in exposure levels is therefore not as rapid as the increase in the number of emitters and services. The evolution of exposure over the years has therefore been regular and we are witnessing an increase in the dynamics of variation, particularly for LTE, for which the variation can be rapid and strong, which needs to be reconsidered with the international reference levels (ICNIRP, 1998). Standardized exposure measurements are punctual and represent the exposure of a given location reasonably well, but they do not provide the variable exposure of someone who, in his daily life, works, goes out, travels, etc. A double measurement makes it possible to both consolidate existing measurement protocols and obtain a large batch of exposure data over the course of a day, with significant disparities between cases of exposure at home, at work, and in transport.

This study had several limitations. The first was that the measured field strengths were not representative of the average values in the urban households of the investigated cities because they were selected to be within 250 m or less from a MPBS and in buildings intersected by the beams from a MPBS. This selection procedure favors a high gradient of exposure to RF-EMF between volunteers, as all the location of the residential units of these buildings were not all at a position intersected by the main beam. The underlying reason was that this exposure study forms part of an epidemiological, cross-sectional study aiming to investigate the association between RF-EMF exposure from MPBSs and health disorders among participants. Furthermore, the selection of antennae resulted in a higher proportion of participants dwelling in tall buildings.

A second limitation was the characterization of places visited by the participants of the PEM survey: neither accurate locations (no GPS) nor descriptions (office, shops, bus station, etc.) were indicated in the diary logs, but only four basic activities, i.e. at home, work, trip, other place.

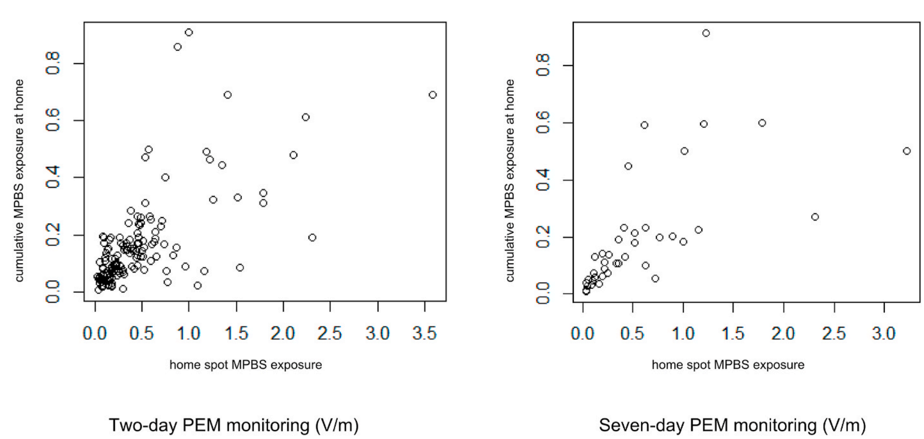

Fig. 1. Comparison between home spot and personal PEM measurements.

Furthermore, the expected number of participants for the two-day survey (n = 240) was not reached and was low. In particular, the low and non-representative number of working participants makes the data concerning the observed lower exposure level at work sites unreliable.

Concerning data processing, the replacement of values below the determination limit by a value of half the detection limit is a general approach already used by Heinrich et al. (2010), introducing uncertainties in the quantitative results.

Another limitation was that the exposure assessment was only based on time-averaged values. Peak values of pulsed waves were not measured, even though they may have a higher impact on health than continuous exposure to the mean values.

Finally, the PEM campaigns were conducted successively in the different cities, from late 2015 to early 2017, which limits the comparison between the different sites because of the possibility of different activities and habits due to the weather.

4.2. Exposure levels compared to those of other publications

The values of the field strengths measured in our study were slightly different from those given in 2014 by the ANRF for all measurements made in France up until then, with a median value of 0.38 V/m and a 90th percentile value of 1.4 V/m versus 0.44 and 1.13 V/m, respectively, in this study. Spot measurements at the participants' homes showed exposure levels to be generally higher than those indicated in other studies using similar methods. The review of Sagar et al. (2018b) reported maximal mean values in households of 0.37 (Tomitsch and Dechant, 2015) in Austria and 0.33 (Vermeeren et al., 2013) in Belgium and Greece. According to a recent review by Chiamarello et al. (2019), the exposure levels measured by spot measurement in the present study were also higher than those indicated by other studies measuring fields in households using a PEM, with the exception of a study in Stockholm targeting an apartment very close to a group of two MPBSs, with measurements made in all parts, including several balconies (Hardell et al., 2018). Other causes of differences between the field strengths measured by spot tests and PEMs can be attributed to uncertainties associated with PEM measurements, such as body shielding, calibration, variations in probe sensitivity with frequency, and other artefacts (Chiaramello et al., 2019).

The dominant proportion of field strengths from MPBSs in home spot measurements was likely due to the participant selection method, which included only urban sites and favored housing close to a MPBS. Another study published in 2012, based on random selection of 1348 German households showed a higher contribution of cordless phone DECT and Wi-Fi (Breckenkamp et al., 2012) in RF-EMF measured by PEMs left at fixed positions. However, such a dominance of DECT frequencies would surely not be found nowadays for the same study, given the recent development of mobile phone use in Belgium and the Netherlands, as observed by Urbinello et al. (2014).

4.3. Variation of exposure level (spot measurements) according to features of the housing

The spot measurements in collective dwellings clearly showed higher field strengths on the highest floors. The increase was not linear but field strengths on the first three floors were at least two times lower that those measured on the sixth floor. This was observed for both fields emitted by total sources and the MPBS for the median, mean, and maximal field-strength values. This trend is consistent with the features of base stations, the shape of wave beams, and the major contribution of the MPBS to RF-EMF field strength. Breckenkamp et al. (2012) showed differences in total field strength from floor to floor in Germany, and Hardell et al. (2018) showed very high field strengths from base stations in an upper-floor apartment in Stockholm. However, the influence of the floor on the exposure of dwellers to RF-EMF has not been investigated with such a large sample of apartments thus far. Moreover, the results confirm that apartments with windows located in front of a MPBS are clearly more exposed than those with a different orientation.

4.4. Variation of exposure level (PEM measurements) according to the period of measurement

The difference between the field strengths measured during the day and night, similarly observed by Frei et al. (2009), can be explained by the fact that active individuals generally move from place to place, along with the fact that low-communication traffic occurs in the late night and early morning, whereas peak traffic, with the highest power radiated by antennas, may occur around noon and in the afternoon or evening (Bürgi et al., 2014). Indeed, the recorded day/night exposure ratio of 1.2 was slightly lower than the day/night ratio of 1.4 between duty factors derived by Bürgi et al. (2014) in the above-mentioned paper, likely because this author considered a larger period of the day (06H–22H) than in the present study (08H–20H).

We found no difference between exposure levels during the work week and weekends. This result is consistent with the low exposure levels measured at the workplace relative to households and during trips (see below). Viel et al. (2011) measured higher field strengths from downlink GSM on Sundays than on working days in France, but lower field strengths from downlink UMTS. Frei et al. (2009) found higher exposure to RF-EMF during work days, but the major contribution came from cordless phone DECT systems. No argument is thus currently available in favor of a difference between weekend and working-day exposure.

4.5. Variation of exposure levels (PEM measurements) according the location/activity of participants

The results of both PEM surveys showed slightly higher exposure levels (mean values) to MPBS frequencies during travel, here defined without distinction between walking, public transport, or car trips. Although many studies have shown that traveling by public transport or in a personal car leads to higher exposure to RF-EMF than other usual personal activities, the main contribution is mainly due to uplink sources, for example the use of mobile phones by passengers and/or position updating by mobile phones on stand-by (Chiaramello et al., 2019; Urbinello and Röösli, 2013). On the other hand, a recent study by Sagar et al. (2018a) showed that uplink transmissions were the most relevant exposure sources in trains, whereas the most relevant source of exposure for other types of vehicles was found to be downlink sources (for example: 0.28 V/m on the bus in rural Switzerland). Gryz et al. (2015) also showed notable exposure to downlink MPBSs (especially GSM, 1800) in the underground in Warsaw, which is a widely used means of transport in Paris, Lyon, and Lille.

Workplaces were designated a few years ago as sites of high exposure to RF-EMF from all sources (Vermeeren et al., 2013). Moreover, Markakis and Samaras (2013) showed that signals from MPBSs are dominant in the workplace and schools in Greece, whereas wireless phones and computer networks are the most influential at home. Our results showing clearly lower field strengths from base stations at the workplace thus differ from those of previous studies and are probably influenced by the selection of households from the upper floors, from which the members frequent workplaces such as shops department stores, bank agencies, schools, health centers, administrative establishments, and small company headquarters.

4.6. Comparison between spot and PEM measurements

The mean values of the electrical fields from base stations measured by spot measurements according to the national French protocol were nearly three times higher than those measured by PEMs worn by the participants staying at home for both the 48-h and seven-day surveys. Aside from the body shielding and other uncertainties associated with

PEM measurements, this ratio reveals that (i) the field strengths from MPBSs can vary significantly inside the same household, and thus indoor spot measurements are not representative of the true cumulative exposure of the inhabitants to these frequencies, and (ii) the standard protocol of the French agency ANRF for indoor RF-EMF measurement complies with the principle of precaution in giving a maximal value for the potential exposure of the inhabitants. On the other hand, exposure levels given by PEM measurements may likely be underestimated, notably because of the body-shielding effect (Chiaramello et al., 2019; Gajsek et al., 2015).

Studies comparing RF-EMF measurement methods are very scarce. Only Frei et al. (2010) conducted such a study in Basel (Switzerland), aiming to compare personal measurements, spot measurements, geo-coded distances from MPBSs, and wave propagation-based prediction models to estimate the level of exposure to RF-EMF. PEM measurements involved 166 participants and lasted one week, and spot measurements included 134 participants. Using the same Spearman statistical test, the authors found a significant correlation between the spot and PEM measurements (0.73; 95%-CI: 0.63 to 0.80). Our results, based on a quite similar number of participants, are hence consistent with those of the Swiss study.

The strong correlation between spot and PEM (48-h and seven-day) measurements reinforces the reliability of the French standard protocol as a means of estimating the exposure to RF-EMF from MPBSs. Although the true exposure levels were overestimated, this measurement method could be developed to monitor future variations of exposure, particularly because PEM measurements are expensive, subject to measurement uncertainties and technical hazards, and time-consuming and because PEMs are less accepted by the population.

5. Conclusion

This study is the first to assess the exposure of people living near a MPBS to RF-EMF in urban areas in France. It shows a significant contribution of MPBSs in the exposure of urban citizens to RF-EMF and that exposure levels are far below the exposure limits recommended by the ICNIRP for heating. Because of the variation of field strengths within housing, spot measurements made according to the French standard protocol of the ANFR aim to estimate the maximal exposure of inhabitants staying at home. On the other hand, exposure measured by PEMs may be underestimated because of body shielding and other sources of uncertainty. However, spot measurements of maximal exposure can be a reliable method to estimate the impact of the evolution of mobile-phone networks and technology on exposure of the population to RF-EMF. Nevertheless, the anticipated development of the 5G network will entail a new protocol for future measurement of exposure to RF-EMF.

Credit author statement

The study was conceived by a working group from the Dialog Committee "Radiofrequencies and health" of the French Agency for Food, Environmental, and Occupational Health & Safety (ANSES), and a Scientific Council (Jean-François Doré, Pierre Ducimetière, Anne-Sophie Evrard and Thierry Letertre) followed its implementation, and reviewed the results as they progressed and the writing of the manuscript. Claire Ségala, Jean-Christian Genier, Pascal De Giudici and Sylvie Martin designed the study. Jean-Christian Genier was responsible for the EMF measurements and for the coordination of the home visits. Pascal De Giudici and Sylvie Martin were responsible for data management and the statistical analysis. Pascal De Giudici was responsible for editing the manuscript with the help of Claire Ségala, Jean-Christian Genier and Sylvie Martin.

A declaration has been made to the French data protection authority (number 1862114).

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Declaration of competing interest

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

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