Children's exposure assessment of radiofrequency fields: comparison between spot and personal measurements

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Abstract

Introduction

Radiofrequency (RF) fields are widely used and, while it is still unknown whether children are more vulnerable to this type of exposure, it is essential to explore their level of exposure in order to conduct adequate epidemiological studies. Personal measurements provide individualized information, but they are costly in terms of time and resources, especially in large epidemiological studies. Other approaches, such as estimation of time-weighted averages (TWAs) based on spot measurements could simplify the work.

Objectives

The aims of this study were to assess RF exposure in the Spanish INMA birth cohort by spot measurements and by personal measurements in the settings where children tend to spend most of their time, i.e., homes, schools and parks; to identify the settings and sources that contribute most to that exposure; and to explore if exposure assessment based on spot measurements is a valid proxy for personal exposure.

Methods

When children were 8 years old, spot measurements were conducted in the principal settings of 104 participants: homes (104), schools and their playgrounds (26) and parks (79). At the same time, personal measurements were taken for a subsample of 50 children during 3 days. Exposure assessment based on personal and on spot measurements were compared both in terms of mean exposures and in exposure-dependent categories by means of Bland-Altman plots, Cohen's kappa and McNemar test.

Results

Median exposure levels ranged from 29.73 (in children's bedrooms) to 200.10 μW/m^2 (in school playgrounds) for spot measurements and were higher outdoors than indoors. Median personal exposure was 52.13 μW/m^2 and median levels of assessments based on spot measurements ranged from 25.46 to 123.21 μW/m^2. Based on spot measurements, the sources that contributed most to the exposure were FM radio, mobile phone downlink and Digital Video Broadcasting-Terrestrial, while indoor and personal sources contributed very little (altogether <20%). Similar distribution was observed with personal measurements.

There was a bias proportional to power density between personal measurements and estimates based on spot measurements, with the latter providing higher exposure estimates. Nevertheless, there were no systematic differences between those methodologies when classifying subjects into exposure categories. Personal measurements of total RF exposure showed low to moderate agreement with home and bedroom spot measurements and agreed better, though moderately, with TWA based on spot measurements in the main settings where children spend time (homes, schools and parks; Kappa = 0.46).

Conclusions

Exposure assessment based on spot measurements could be a feasible proxy to rank personal RF exposure in children population, providing that all relevant locations are being measured.

Keywords: Exposure assessment; Electromagnetic fields; Radiofrequencies; Children

Abbreviations

RF: Radiofrequency; TWA: time-weighted averages; INMA: Environment and childhood (from INfancia y Medio Ambiente) cohort; DVB-T: Digital Video Broadcasting-Terrestrial; LOQ: limit of quantification; DECT: Digital Enhanced Cordless Telecommunications; Uplink: Mobile phone uplink; Downlink: Mobile phone downlink

1. Introduction

Radiofrequency (RF) fields cover the frequency range between 10 MHz and 300 GHz and are mainly used for wireless communication purposes (World Health Organization, 2016). Sources of this type of electromagnetic field are growing and hence, there is a need for research into exposure assessment to guide the design of high quality epidemiological studies. In addition, further research on the characteristics of RF exposure, such as, assessment of exposure levels from emerging sources, quantification of personal exposure levels, and prospective studies of children and adolescents are considered high priority research needs by the World Health Organization, (2010).

Whether children are more vulnerable than adults to RF exposure is still being discussed (Foster and Chou, 2014; IEGMP. Independent Expert Group on Mobile Phones, 2000; Van Rongen et al., 2004) but it is expected that present-day children and adolescents will have longer lifetime exposure than present-day adults. In addition, children’s exposure profile, determinants of exposure and contribution of sources may vary from those of adults’.

To date, many epidemiological studies assessing health effects of RF exposure have been focused on specific sources, such as use of mobile or cordless phones (Abramson et al., 2009; Aydin et al., 2011b; Cardis, 2010; Divan et al., 2008; Redmayne et al., 2013; Sadetzki et al., 2014; Schüz et al., 2011; Thomas et al., 2010) (most of them considering self-reported use), and on distance to some far-field sources (mobile phone base stations, television and radio antennas, whose radiation is contributing to people’s exposure in the far field of the source) (Dode et al., 2011; Wolf and Wolf, 2004). These methods to assess exposure have limitations. Specifically, self-reporting of phone use has been proven to over- or under-estimate exposure sufficiently that it can lead to misclassification (Aydin et al., 2011a; Roser et al., 2015; Schüz et al., 2011) and distance per se to far-field sources has been considered an inadequate surrogate for exposure assessment (Gonzalez-Rubio et al., 2016), showing moderate (Beekhuizen et al., 2015) or low (Neitzke et al., 2007) association with exposure from mobile phone base stations and also a very low correlation with personal measurements of total RF exposure (Frei et al., 2010). Recently, efforts have been made to achieve more comprehensive exposure assessment. Many authors have tried to assess exposure by performing measurements (spot or personal) (Calvente et al., 2015; Roser et al., 2017) or by using simulations to predict such exposure (Beekhuizen et al., 2014; Bürgi et al., 2008). Nevertheless, few studies have reported data on RF exposure on children or adolescents, combining exposure from near- and far-field sources (Roser et al., 2015). Further, there is still no accepted standardized method for comprehensively assessing realistic exposure to RF fields of general public for epidemiological purposes. Personal measurements provide individualized information and consider temporal and spatial variations, but require substantially greater effort in terms of time and resources, especially in large epidemiological studies. Assessing exposure based on spot measurements may be an alternative and a proxy for personal exposure assessment. Besides, while personal measurements may be more prone to random variability or to variability introduced by specific activities, spot measurements may be better replicated and thus they could better reflect longer-term exposure at the specific sites.

Although personal measurements have been found to be moderately correlated with simulated exposure (Frei et al., 2010; Martens et al., 2016, 2015), to our knowledge, there is a lack of studies assessing agreement between personal measurements and exposure assessment based on spot measurements in the main settings of the participants. Filling this gap in the literature could help to establish whether spot measurements can be used as a proxy for personal exposure levels, which is important, as this approach would simplify research and make it more feasible to cover larger populations.

The aims of this study were to assess RF exposure in the INMA-Gipuzkoa (*Infancia y Medio Ambiente*-Environment and childhood) birth cohort (www.proyectoinma.com)

(Guxens et al., 2012), by spot measurements and personal measurements in the settings where children tend to spend most of their time, i.e., homes, schools and parks; to identify the settings and sources that contribute most to that exposure; and to explore if exposure assessment based on spot measurements is a valid proxy for personal exposure.

2. Material and Methods

2.1. Study population

This study was embedded in the INMA-Gipuzkoa birth cohort which is located in the Basque Country and is part of a Spanish multicenter study (Guxens et al., 2012).

The recruitment of mother-child pairs took place during the first antenatal visit (10-13 weeks of gestation) to the physician in the public referral hospital (Zumarraga hospital) between April 2006 and January 2008.

In total, 638 out of 993 mother-child pairs invited to participate met the inclusion criteria and agreed to be enrolled in the INMA-Gipuzkoa study. This study was conducted over the period 2014-2016, when the children reached 8 years of age, all cohort members were contacted; at that time, 397 children (62.2%) participated in the study.

2.2. Study procedure

2.2.1. Measurement devices

For measuring narrowband RF fields in the 87.5 MHz–6 GHz range, we used an ExpoM-RF 3 (hereinafter ExpoM) personal portable exposimeter (Fields at work, Zurich, Switzerland, 2017). This device measures exposure to 16 different frequency bands according to emissions from different main sources: FM Radio; Digital Video

Broadcasting-Terrestrial (DVB-T); LTE 800 uplink and downlink (LTE 800 UL and LTE 800 DL respectively, used for 4G); GSM 900 uplink and downlink (GSM 900 UL and GSM 900 DL, used for 2G); GSM 1800 uplink and downlink (GSM 1800 UL and GSM 1800 DL, used for 2G/4G); Digital Enhanced Cordless Telecommunications (DECT); UMTS uplink and downlink (UMTS UL and UMTS DL, used for 3G); ISM 2.4 GHz (used for WiFi); LTE 2600 uplink and downlink (LTE 2600 UL and LTE 2600 DL, used for 4G); WiMax 3.5 GHz (used for wireless internet connection mainly in rural areas); and ISM 5.8 GHz (used for WiFi). Measurement ranges are displayed in Supplementary Table 1. This meter uses a three-axis isotropic antenna. The ExpoM was calibrated by the manufacturers prior to the measurement campaign, and every 6 months during the measurement campaign, to ensure good working conditions.

2.2.2. Measurement procedure

The procedure is explained in detail in a previous publication (Gallastegi et al., 2016). In brief, we conducted measurements in the settings where children spent most of their time, which are homes, schools and parks (Basque Government, 2017). In the case of homes, measurements were taken in the living room and child´s bedroom in 104 households which were selected mainly on their availability since most of the mothers (386 of 397 contacted, 97.2%) agreed to measurements being taken in their home. All primary schools in the study area (N=26) were included in the measurement campaign and, in each school, the main playground and the two classrooms for each year group (second and third year of primary school) with the most of INMA students were chosen for performing the measurements. The parents selected the parks or other public spaces (hereinafter “parks”) where their children spent most of the time from a list of parks provided to them, and also ranked these places by the amount of time spent there. RF measurements were taken in a subset of all the parks in the study area (79/125, 63.2%), including those most frequently selected by parents.

The measurement procedure varied as a function of the environment (indoor or outdoor) (Supplementary Table 2). For indoor settings, procedure described by Frei et al. (2010) was followed, which was based on the adaptation of Bürgi et al. (2009) for the European Standard EN 50492 (CENELEC, 2008). We performed three narrowband indoor measurements at the center at different heights and one in each of the four corners of each room (living rooms, children´s rooms and classrooms), and one outdoor measurement at the center of the spaces (playgrounds and parks). The device was held in a non-conducting tripod which was adjustable to the desired height. Mobile phone use was not allowed in the room where spot measurements were taken. In addition, in order to conduct personal measurements, a subsample of 50 children (randomly selected among the 104 with measurements at home) carried the exposimeter with them for 3 whole days with a measurement time-interval of 4-seconds. During the day the device was placed in a padded belt bag around their waist. At night, children placed the device on a flat non-metallic surface, as close as possible to their bed. In order to ensure that the battery of the device lasted, it had to be charged every night during sleeping-hours of the children.

All spot measurements were conducted from Monday to Friday (weekdays), with school measurements being performed during school-hours, while personal measurements could include weekend days, but captured exposure from at least one weekday.

2.2.3. Data handling and statistical analysis

No significant differences were identified regarding relevant characteristics (sociodemographic characteristics and variables concerning potential RF sources) between the subsample selected for personal measurements (two subjects were discarded due to problems with the device, n=48) and the whole subsample with in-home measurements (n=104) (Supplementary table 3); and between the subsample with in-home measurements and the full cohort (Gallastegi et al., 2017). The device provided data on electric fields. For each setting, a variable number of readings were obtained as a function of the measurement time-interval set (4 s) and the duration of the measurement. We assigned values of half the limit of quantification (LOQ) to readings below this limit and the upper limit to readings above the upper range. Substitution methods of censored data are often used in the epidemiological literature (Hewett and Ganser, 2007). Subsequently, data were converted to power density (μW/m^2), for the assessment of exposure. In the case of spot measurements and following the procedure described by Frei et al., (2010), the mean for each room and for each of the bands was calculated. Similarly, mean of readings obtained in each outdoor setting was calculated in power density. During personal measurements, while the participants charged the ExpoM, the battery cable acted as an antenna, resulting in an overestimation of FM radio exposure. This error was corrected by replacing data by median exposure values obtained under the same conditions, i.e., when the exposimeter was at home, but was not charging. Whether the device was charging was specified in the results output.

Most of the RF sources were categorized into groups in order to assess their contribution to the total exposure and the sum between sources was done in electric field magnitude for each of the readings by the square of the quadratic mean. Broadcast sources corresponded to FM radio and DVB-T bands. Mobile phone uplink (uplink) sums results for all uplink bands (ascendant union, from devices to the antenna), i.e., LTE 800, GSM 900, GSM 1800, UMTS and LTE 2600, and mobile phone downlink (downlink) all downlink bands (descendant union, from antenna to the devices), i.e., LTE 800 GSM 900, GSM 1800, UMTS and LTE 2600. For wireless internet connection we have only considered the 2.4 GHz band, given that harmonics generated by signals around 1800 and 900 MHz interfere in the readings of 5.8 GHz WiFi and given that other wireless internet sources (5.8 GHz band and WiMax 3.5

GHz) are rarely present (out of the 442 settings where we conducted measurements only 2.3 and 1.1% showed mean levels above LOQ for 5.8 GHz and 3.5 GHz, respectively). Those two internet bands were also excluded for the calculation of total exposure and the only wireless internet source considered was the 2.4 GHz band.

Differences between settings were checked by non-parametric Mann-Whitney U (indoor/outdoor) and Kruskal-Wallis (homes/classrooms/school-playgrounds/parks) tests because exposure levels did not show a normal distribution.

We employed several approaches based on spot measurements for assessing children's RF exposure. On the one hand, we used average exposure levels measured in specific settings to estimate individual exposure as follows:

a) average exposure levels found in each home (including measurements in bedroom and living room) by spot measurements; herein, home measurements;

b) average exposure levels found in each bedroom by spot measurements; herein, bedroom measurements;

c) average exposure levels found in each living room by spot measurements; herein, living room measurements;

On the other hand, time-weighted averages (TWAs) were calculated for each participant taking into account hours spent at home, at school and in parks together with the exposure levels obtained by spot measurements in those settings. For this purpose, we used the information that parents reported in questionnaires regarding time spent in each setting, making different adjustments:

d) TWA based on considering the same number of hours spent in each setting for all the children (median value of the total hours reported by parents of all participants), adjusted to 24 hours, hereinafter, median TWA-adjusted;

e) TWA based on the number of hours that each child spent in the settings as reported by their parents adjusted to 24 hours, herein, own TWA-adjusted;

f) TWA based on the same procedure as "e", but not adjusted to 24 hours; herein, own TWA-unadjusted.

Spearman correlations were calculated between personal measurements and each of the approaches for the 48 children with both types of measurements. Agreement between the different approaches (taking personal measurements as the reference and considering all approaches as continuous variables) was assessed using Bland-Altman plots (Bland and Altman, 1986). In addition, children were classified into three exposure categories (low, medium and high) with a cut off at median and 90^{th} percentile based on their personal and spot measurements in correspondence to previous studies (Frei et al., 2010; Huss et al., 2015). Agreement between group assignment using personal and spot measurements were compared by means of Cohen's kappa coefficient. Further, the McNemar test was used to assess whether there was a systematic difference between the results obtained with each approach compared to personal measurements.

Data were analyzed with Stata (version 14.1; StataCorp, College Station, TX, USA) and SPSS (version 19).

3. Results

3.1. Exposure levels

Median exposures ranged from 29.73 (in children's bedrooms) to 200.10 $\mu W/m^2$ (in school playgrounds) for spot measurements (Table 1). The highest total exposure of 36.94 mW/m^2 was found for a school, an extreme outlier attributed to it having a radio antenna on the roof. The second highest spot measurement value was found in a park (14.81 mW/m^2), and in general terms, exposure levels were higher outdoors than indoors ($p<0.001$). In line with this, broadcast and downlink readings were higher outdoors ($p<0.001$). Uplink readings were more similar for indoor and outdoor measurements ($p=0.882$), and child´s rooms and school playgrounds were the settings with the lowest readings for this type of source. WiFi and DECT readings were higher indoors ($p<0.001$) and the latter was only notable in living rooms (mean±sd/median:

2.43±16.25/0.08 μW/m^2). Higher WiFi readings were found in homes (especially in living rooms; mean±sd/median 12.7±80.03/2.92 μW/m^2) than in classrooms (mean±sd/median 2.33±1.29/1.74 μW/m^2) ($p<.001$).

Median personal exposure was 52.13 μW/m^2 and median exposure for approaches based on spot measurements ranged from 25.46 to 123.21 μW/m^2 (Table 2).

Regarding non-detects, a large proportion was found for some of the bands. Specifically, more than 75% of readings from all bands of uplink were below LOQ, and GSM1800 and LTE2600 uplink were the bands with more readings below LOQ. Proportion of non-detects in downlink bands depends greatly on the band, with just 10% and 26% of readings below LOQ for GSM900 and UMTS respectively, and more than 60% for the rest of the downlink bands. In the case of WiFi (ISM 2.4), FM radio and DVB-T up to 60%, 23% and 4% of all readings were below LOQ, respectively.

3.2. Contribution of the sources

The contributions of the different sources are displayed in Figure 1. In both types of measurements –spot and personal- FM radio, downlink and DVB-T were the sources that contributed most to exposure, although, in personal measurements, the contribution of broadcast frequencies was slightly lower and mobile phone uplink frequencies somewhat higher than in the spot measurements. In contrast, median contribution of mobile phone uplink to total RF exposure was 4.5% and WiFi, and cordless communication (DECT) altogether contributed less than 3%. The contribution of the sources followed a similar pattern across different settings (data not shown).

3.3. Comparison between personal measurements and approaches based on spot measurements

When considering mean and median values, exposure based on home and living room measurements were the assessment that yielded the most similar results to personal measurements respectively (home measurements were 1.09 and 1.49 times higher for mean and median respectively and living room measurements were 0.98 times lower), while own TWA-adjusted and own TWA-unadjusted were the most different, resulting in an overestimation of exposure (Table 2). However, lowest Spearman correlations were found between personal and living room measurements (0.52) and highest for the approach called median TWA-adjusted (Table 2). Although correlations were moderate to strong, Bland-Altman plots showed that approaches based on spot measurements tended to overestimate exposure compared to personal measurements (Figure 2). In addition, the confidence interval (95%) of the mean difference between methods did not span zero. The plots revealed that there was a bias between personal measurements and all of the other approaches for absolute values that was proportional to power density.

Agreements between personal measurements and the different approaches based on spot measurements when classifying the participants into low, medium or high exposure groups are provided in Table 3 (categories of sources). For total RF exposure, median TWA-adjusted was the approach that agreed most closely with personal measurements while bedroom measurements showed the least agreement. Even though the agreement between personal total mean and home measurements was good (64.6%), Cohen´s kappa was moderate (0.39). For uplink exposure, there was no agreement between personal measurements and any of the approaches based on spot measurements. Personal downlink exposure was found to agree better, though moderately, with home measurements and with the median TWA-adjusted. For broadcast exposure, somewhat higher agreement, but still moderate, was found between personal measurement and all of the spot-based TWA approaches. Similar patterns were observed for the separate bands (Supplementary Table 4), spot home measurements agreed moderately well in most cases, and the agreement was better than that found between personal measurements and bedroom or living room-only spot measurements.

An assessment of possible systematic differences between the results obtained with each method based on spot measurements and personal measurements is provided in Supplementary Table 5. There were no systematic differences between personal measurements and any of the other approaches based on spot measurements used for any of the sources.

4. Discussion

In this study we assessed RF exposure levels of a child population by several approaches. We conducted spot measurements in settings where children tend to spend most of their time and we compared results based on those measurements with those of personal measurements, which require greater efforts in terms of time and money. Median exposure for personal measurements was 52.13 μW/m^2 and ranged from 25.46 to 123.21 μW/m^2 for assessments based on spot measurements and from 29.73 to 200.10 μW/m^2 for spot measurements in the different settings. Based on both measurements, broadcast and mobile phone downlink were the sources that contributed most to total exposure. Highest though moderate kappa coefficient (0.46) was found between personal measurements and TWA based on spot measurements and on median number of hours reported for each setting (median TWA-adjusted).

A few studies have assessed exposure levels of children' or adolescents' (Bhatt et al., 2016a; Roser et al., 2017; Thomas et al., 2008; Valič et al., 2014; Verloock et al., 2014; Vermeeren et al., 2013), although, to our knowledge, ours is the first reporting spot measurements in the main places where children spend the most time in their daily lives, along with personal measurements in a subsample.

One of the strengths of the study has been including exposure assessment in schools. Few studies have assessed exposure levels in schools, despite the fact that children spend approximately a quarter of the day and around half the days of the year there. Our total mean (119.51 μW/m^2) is higher than that found by Roser et al., (2017b) in Swiss schools (59.6 μW/m^2) and by van Wel et al., (2017) in Dutch schools (70.5

μW/m^2). The latter used a similar methodology, though they conducted the measurements after school hours and therefore assumed that they would be underestimating exposure. Our median (81.10 μW/m^2) was similar, though somewhat lower, than that observed in Australian schools (0.179 V/m; 84.99 μW/m^2) (Bhatt et al., 2016a). In contrast, Verloock et al., (2014) and Vermeeren et al., (2013) found much higher levels (from 0.34 V/m [306.63 μW/m^2] in Belgium to 0.40 V/m [424.40 μW/m^2] in Greece), but it should be noted that they selected the schools for their proximity to potential sources like WiFi connection, DECT stations, broadcast transmitters and/or telecommunication base stations.

One of the limitations of this study was that even with a very sensitive device, readings from some sources were often (LTE 2600 UL; LTE 2600 DL) or almost always (WiMax 3.5; ISM 5.8) below the LOQ for both spot and personal measurements. In addition to concerns about LOQs, all the measuring devices may be affected by crosstalk, which is an out of band response and occurs when a signal in a specific frequency band is also erroneously registered by another band. This can occur either because some frequency bands are quite close to each other (GSM1800DL, DECT and UMTS UL) (Lauer et al., 2012) or because harmonics of a frequency band have effects in other bands, specifically, harmonics of signals around 1800 MHz and sometimes 900 MHz cause crosstalk in 5 GHz WiFi (Bhatt et al., 2016b). Regarding the former, in this study, we took no specific measures, given that we considered this to be less of a problem with ExpoM than previous portable devices (ExpoM´s crosstalk is between -40 and -60 dB). Regarding the latter, we opted to consider only the 2.4 GHz signal for the wireless internet exposure estimate as the majority of wireless connection systems in our setting use this band. However, given that our measurement campaign ended in the beginning of 2016, when use of 5.8 GHz WiFi started to extend in the study area, a higher contribution of this band could be expected now.

Besides, we based on number of hours reported by parents in the questionnaires for calculating TWAs, which could induce bias in the exposure levels and classification. As other authors have indicated (Klous et al., 2017), participants may underestimate the amount of time spent at home. In fact, there was a mean difference of 2±4 hours between the actual time spent at home (as recorded in diaries completed during personal measurements) and that reported by parents in questionnaires. Those diaries were only available for the subsample with personal measurements (50 participants). In addition, even if the diaries are completed during personal measurements, and thus, recall bias could be minimized, they refer only to those three days with measurements, while schedule reported in the questionnaires refers to usual average timing.

In addition, children in the sample were smaller than some of the heights selected for measurements (1.5 and 1.7 m). However, we followed the procedure reported previously by Frei et al. (2010), which was based on the adaptation of Bürgi et al. (2009) for the European Standard EN 50492 (CENELEC 2008). The procedure was set as the protocol to follow in all the cohorts belonging to the GERoNiMO project (Generalized EMF Research using Novel Methods) in order to have comparable data between different regions of the project.

Mean and median personal total exposure levels (169.19 and 52.13 μW/m^2), were within the range of previously reported values that ranged from 63.2 to 204 μW/m^2 (mean) and from 25.5 to 92 μW/m^2 (median) (Bolte and Eikelboom, 2012; Frei et al., 2009; Roser et al., 2017).

In line with other studies (Joseph et al., 2010; Verloock et al., 2014) RF exposure from outdoor environmental sources was higher outdoors than indoors. In this context, we should note that one school out of 26 in the study area, had its own radio antenna on the roof, which was in continuous operation, and this explains the very high FM Radio exposure levels found in a classroom of that school (36.94 mW/m^2). Interestingly, another school also had its own radio antenna, but in this case spot FM readings were within the 75th percentile (84.50 μW/m^2). For typical indoor environmental sources, such as WiFi and DECT, readings were higher indoors than outdoors, although still very low, in line with previous research (Verloock et al., 2014). It is important to state that in our study area, outdoor WiFi hotspots are not yet very common. WiFi exposure was higher in homes than in schools. DECT exposure was almost negligible and, as expected, highest in living rooms.

Regarding the contribution of sources, FM Radio was the one that contributed most, followed by downlink and DVB-T bands. This pattern was consistent in all settings and for both spot and personal measurements. Sources for personal use (uplink, WiFi and DECT) contributed in total less than 20% to the total exposure. In contrast, in a recent review, the authors observed that downlink and DECT were the sources that contributed most to RF exposure in homes (Sagar et al., 2017) with small contributions from radio and TV-signals. While Beekhuizen et al., (2014) found that indoors TV and radio contributed 7% and 6% respectively, we found median contribution of as much as 55%. As in other studies (Beekhuizen et al., 2014), mobile phone use was not allowed during the spot measurements. Therefore, the contribution of the uplink in spot measurements is not representative of usual levels. In contrast, in previous personal measurement studies, contribution of uplink was predominant together with downlink and DECT (Bolte and Eikelboom, 2012; Frei et al., 2009) in adults and in the case of adolescents 67.2% of exposure was found to come from uplink (Roser et al., 2017). According to this, we would expect the same to be observed in our study, but the difference in uplink contribution between the two approaches (spot and personal) was up to 6% (median and mean contributions to the personal measurements were 4.5% and 9.5%). Only 2 (4.1%) children that conducted valid personal measurements reported using a mobile phone regularly (at least once a week), but our participants were younger (8 years old) than those of Roser´s study (13-17 years old). Therefore, the uplink contribution in our personal measurements can be mainly attributed to the emissions of mobile phones of parents and other adults close to children. We consider that this underlines the relevance of personal use of phones to uplink exposure, which is greater than any exposure due to other people´s use of phones. An exception could be on public transport where other authors have found uplink to contribute most to total exposure (Joseph et al., 2010; Urbinello and Röösli, 2012). Nevertheless, our sample of children did not tend to travel in public transport shared with other adults (trains/buses) where background uplink levels are high.

Given the lack of a standardized and widely accepted method to assess exposure to RF fields for epidemiological purposes, the methodology used varies greatly between studies. In recent years, geospatial models have been used as a surrogate for environmental exposure from mobile phone base stations or broadcast stations. Some authors have compared exposure levels obtained by such models with personal measurements at home (Martens et al., 2015) and spot measurements at home (Beekhuizen et al., 2014; Frei et al., 2010; Martens et al., 2016) in adult populations. However, they have focused only on downlink exposure.

Our study population is composed of children, and the amount of time they tend to spend in each type of setting, including home, may vary from patterns in adults. We assume that children usually have more structured daily habits. Therefore, it could be easier to identify the settings where they spend most of their time during the day; this would be useful in determining the most relevant settings for spot measurements, and in turn, in case of good agreement with personal measurements, would simplify the work related to exposure assessment. However, it should be noted that whether spot measurements simplify or not the assessment depends on the protocol. In our study, around 30 times more hours were invested for assessing exposure of 50 children by personal measurements compared to assessing by spot measurements. On the other hand, methodologies such as car-mounted measurements (Bolte et al., 2016) or measurements using drones (Joseph et al., 2016) would also considerably reduce time required, but these methodologies are not suitable for indoor environments, and therefore would not make possible to capture exposure from settings where children spend most of their time (homes and schools). In our study, total personal RF levels showed greatest similarity with home measurements in terms of average exposure. In contrast, highest Spearman correlation was found between personal and median TWA-adjusted (0.72) and lowest between personal and measurements in the living room (0.52). This suggest that even both personal and home measurements result in lower exposures than the TWAs, conducting measurements only in homes would lead to misclassification of personal exposure. Observing differences between personal total values and other exposure estimations by Bland-Altman plots revealed that approaches based on spot measurements overestimated exposure compared to personal measurements. In addition, difference increased with the increasing mean power density, this implying that differences between personal and the rest of the methods were power density-dependent. Nevertheless, given that in epidemiological studies the correct ranking of exposure is considered more important than precise values (Kheifets and Oksuzyan, 2008), we compared the different approaches employed by classifying individuals into exposure categories, as it has previously been used for children (Huss et al., 2015) and adults (Frei et al., 2010). Frei et al., (2010) found a moderate Spearman correlation (0.42) between personal and spot measurements in bedrooms for total RF exposure. In our study, agreement between exposure classification based on personal measurements and on each of the other approaches varied from 0.25 (spot measurements in bedrooms) to 0.46 (median TWA-adjusted). On the one hand, this would mean that median TWA-adjusted might be useful as a simple approach with which replace personal measurements. On the other hand, even if the bedroom is the place where children spend most time each day, conducting measurements only in bedrooms would lead to considerable misclassification when ranking study participants based on their exposure levels. Nonetheless, neither of the approaches led to a systematically different total exposure classification compared to the classification obtained by personal measurements. In general, median TWA-adjusted showed the best (but still moderate) agreement coefficients, with personal measurements. In contrast, when examining source by source, classification obtained by at home measurements showed the best agreement (coefficients of as high as 0.75 for DVB-T). No agreement was observed between classification based on personal measurement and that based on any of the other proxies in the case of uplink. It is important to underline, however, that when measurements were taken at home all RF emitting devices were required to be set as usual, but measurements were conducted without anyone in the rooms being measured, and hence, uplink levels at homes may not be representative of real exposure levels. Still, in both personal and spot measurements uplink made a minor contribution to total exposure.

All the methodologies used for RF exposure assessment have limitations. Exposure estimation based on spot measurements can be inadequate, as long as such measurements are only taken over a specific period of time, at a specific location and under specific circumstances regarding use of sources in the surroundings. Still, small temporal variations have been observed during daytime hours in earlier studies (Manassas et al., 2012), while differences have been more pronounced between day- and night-hours with higher exposures during the day (Manassas et al., 2012; Roser et al., 2017; Sagar et al., 2017; Vermeeren et al., 2013). Few studies have reported differences on exposure levels between weekdays and weekends and no robust conclusions can be drawn yet. Some authors have not found differences between both periods (Frei et al., 2009; Manassas et al., 2012) or have observed somewhat higher total RF exposures on weekends (Roser et al., 2017) or on Sundays (Viel et al., 2011) compared to the rest of the week, though exposure differences varies upon the frequency bands (Viel et al., 2011). In contrast, Bolte and Eikelboom found 80% higher total RF exposures during worked-days than during non-worked days (Bolte and Eikelboom, 2012). Conducting spot measurements in weekends is not as suitable as in weekdays, especially in indoor places like homes and schools. Given that one of the advantages of assessing exposure with spot measurements would be simplifying the field work, in this study we compared personal measurements that could include also weekend days with spot measurements that were only performed during weekdays. Thus, we did not take into account possible variation between weekdays and weekends. On the other hand, even if we assume that personal measurements are the ones that best capture the personal exposure in terms of time and spatial variations, they also present limitations, due to changes in behaviors of participants and the effect of body shielding on the readings (Bolte et al., 2011; Frei et al., 2010). Thus our results could also be interpreted as an underestimation of exposure by personal measurements compared to spot measurements, which was previously supported by other authors (Neubauer et al., 2007). In any case, our results suggest that spot measurements could replace individualized and more comprehensive measurements, like the personal ones, in children in which the uplink contribution is still not relevant and if based on all relevant locations.

5. Conclusions

We assessed children´s RF exposure by several different approaches based on spot measurements and by personal measurements. Higher total RF levels were observed outdoors. Based on both approaches, broadcast and mobile phone downlink were the sources that contributed most, while mobile phone uplink and other indoor sources like WiFi or DECT made only minor contributions. Total personal average RF levels were most similar to measurements obtained in homes, but lowest Spearman correlation was found between personal measurements and homes (especially in living rooms). There was a proportional bias between personal and approaches based on spot measurements, the latter overestimating exposure compared to personal measurements. On the other hand, there were no systematic differences between personal measurements and other approaches when classifying children into exposure categories. Personal measurements for total RF agreed better, although only moderately well, with exposure estimates based on spot measurements in the main settings (homes, schools and parks) and taking into account overall median time spent in each setting considering times reported by all participants. Therefore, using TWA based on spot measurements could be a feasible proxy to rank personal RF exposure in children population, providing that they do not use the mobile phone frequently and that all relevant locations where children spend their time are captured.

Competing interests

The authors declare no conflict of interest.

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Ethical declaration

Prior to children's inclusion in the study, their legal guardians provided written informed consent. The research has been performed in accordance with the Spanish Law 14/2007 on Biomedical Research and the ethical principles of the Declaration of Helsinki. This work has been approved by the ethical committee of the Basque Country (CEIC-E).

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Table 1: Descriptive statistics of total radiofrequency exposure levels by spot and personal measurements

	N	Mean (SD)	Geometric mean (GSD)	Median (IQR)	P90	Minimum	Maximum
Homes							
Child´s room	104	99.14 (162.44)	35.79 (4.33)	29.73 (13.06-111.33)	298.60	2.74	1034.68
Living room	104	195.69 (639.37)	54.30 (4.70)	51.60 (17.29-170.25)	315.28	2.75	6307.44
School							
Classrooms	26[a]	1535.77 (7222.74)	77.67 (6.19)	82.80 (21.44-184.31)	362.89	2.77	36942.15
Classrooms[b]	25[a]	119.51 (135.61)	60.69 (3.84)	81.10 (21.44-181.44)	224.87	2.77	603.22
Playground	26	255.62 (244.38)	157.34 (3.07)	200.10 (97.32-290.51)	655.86	9.28	950.74
Parks	78	623.31 (1895.78)	154.91 (4.36)	122.96 (47.98-364.58)	1349.06	12.88	14806.83
Personal measurements	48[c]	169.19 (720.70)	50.14 (3.09)	52.13 (24.87-84.17)	201.75	2.88	5042.77

All values are given in power density, $\mu W/m^2$; SD: standard deviation; GSD: geometric standard deviation; IQR: interquartile range; P90: 90th percentile; [a]Average of the two classrooms from each school; [b]Data for one school was omitted from this calculation, since it was an extreme outlier; [c]Two measurements out of 50 had to be omitted due to technical problems

Table 2: Descriptive statistics of children's daily exposure estimates by different methodologies

	N[a]	Mean (SD)	Geometric mean (GSD)	Median (IQR)	P90	Minimum	Maximum	rho[b]
Personal measurements	48	169.19 (720.66)	50.14 (3.09)	52.13 (24.87- 84.17)	201.75	2.88	5042.77	-
Homes	48	183.62 (466.58)	56.02 (4.73)	77.76 (14.51-164.08)	360.91	3.50	3173.04	0.64
Bedroom measurements	48	115.08 (195.48)	37.82 (4.66)	25.46 (12.77-118.80)	329.23	2.74	1034.68	0.58
Living room measurements	48	252.15 (911.83)	55.25 (5.18)	51.34 (16.46-179.76)	295.21	2.82	6307.44	0.52
Median TWA-adjusted[c]	48	381.57 (1308.35)	120.63 (3.34)	123.21 (55.62- 215.08)	509.83	14.58	8941.53	0.72
Own TWA-adjusted[d]	47[e]	412.13 (1828.98)	91.75 (4.03)	105.86 (42.01-196.32)	518.23	1.45	12635.77	0.60
Own TWA-unadjusted[f]	47[e]	500.27 (2197.41)	118.99 (3.50)	119.56 (53.19-224.02)	530.58	15.47	15162.93	0.67

Calculations are performed only for the subsample with both personal and spot measurements; All values are given in power density ($\mu W/m^2$); TWA: time-weighted average; SD: standard deviation; GSD: geometric standard deviation; IQR: interquartile range; P90: 90th percentile; rho: Spearman's rank correlation coefficient; For the calculation of TWAs, we assigned the same exposure levels in schools to all children studying in the same school, by averaging the mean exposure levels found in the two classrooms selected; [a]Two out of 50 personal measurements had to be omitted due to technical problems; [b]Spearman correlations were calculated between personal measurements and each of the approaches based on spot measurements for the 48 children with both types of measurements; [c]based on spot measurements and on median hours reported by parents for each setting; [d]based on spot measurements and on hours reported by parents for each setting; [e]for one child, no questions were completed regarding number of hours spent in each setting; [f]based on spot measurements and hours specified in questionnaires by parents (total hours reported by each one, not necessarily 24 hours)

Table 3: Agreement between exposure classification obtained by personal measurements and other approaches based on spot measurements

	Home measurements[a]		Bedroom measurements[a]		Living room measurements[a]		Median TWA-adjusted[a]		Own TWA-adjusted[b]		Own TWA-unadjusted[b]	
	Agreement (expected)	K[c]	Agreement (expected)	K[c]	Agreement (expected)	K[c]	Agreement (expected)	K[c]	Agreement (expected)	K[c]	Agreement (expected)	K[c]
DECT	68.75 (41.75)	0.46	41.67 (36.55)	0.08	56.25 (41.75)	0.25	60.42 (41.75)	0.32	59.57 (41.42)	0.31	59.57 (41.42)	0.31
WiFi[d]	52.08 (41.75)	0.18	39.58 (41.75)	-0.04	47.92 (41.75)	0.11	47.92 (41.75)	0.11	53.19 (41.42)	0.20	48.94 (41.42)	0.13
Broadcast	64.58 (41.75)	0.39	58.33 (41.75)	0.28	62.50 (41.75)	0.36	70.83 (41.75)	0.50	70.21 (41.42)	0.49	65.96 (41.42)	0.42
Downlink	68.75 (41.75)	0.46	62.50 (41.75)	0.36	58.33 (41.75)	0.28	66.67 (41.75)	0.43	61.70 (41.42)	0.35	61.70 (41.42)	0.35
Uplink	37.50 (41.75)	-0.07	52.08 (41.75)	0.18	41.67 (41.75)	-0.00	39.58 (41.75)	-0.04	48.94 (41.42)	0.13	40.43 (41.42)	-0.02
Total	64.58 (41.75)	0.39	56.25 (41.75)	0.25	60.42 (41.75)	0.32	68.75 (41.75)	0.46	63.83 (41.42)	0.38	63.83 (41.42)	0.38

[a]Cohen´s kappa was performed for 48 participants with complete information on personal and spot measurements; [b]Cohen´s kappa was calculated for 47 children that had complete questionnaire data; [c]Cohen´s kappa; [d]Only ISM 2.4 GHz was taken into account.

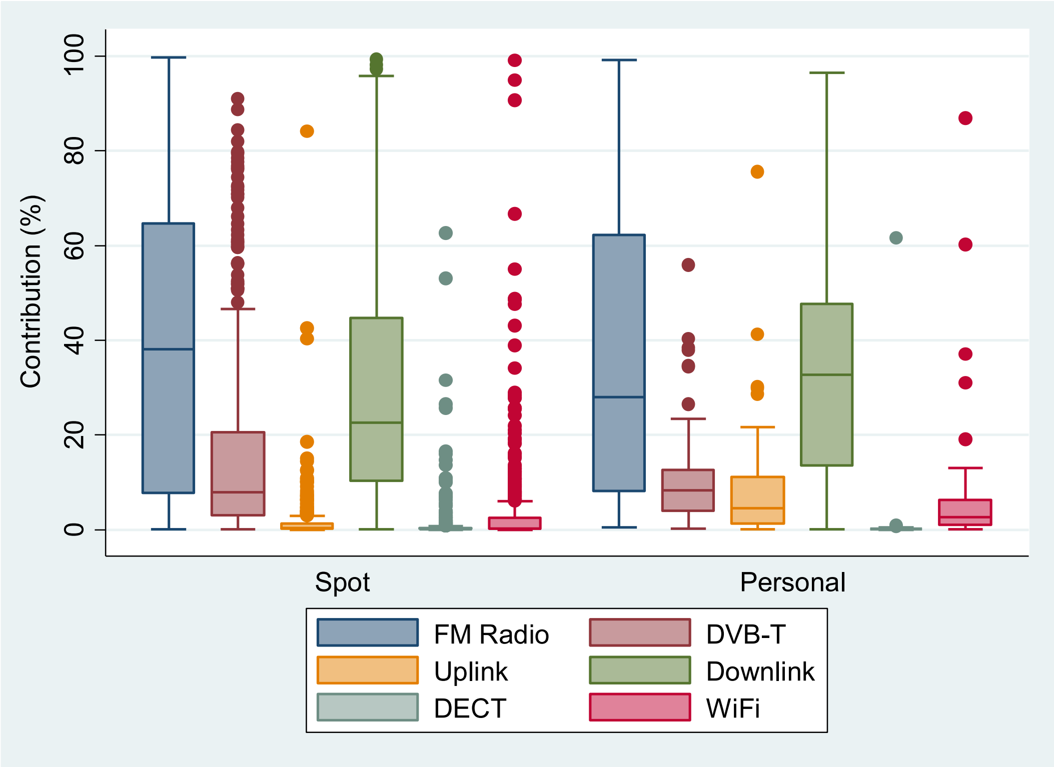
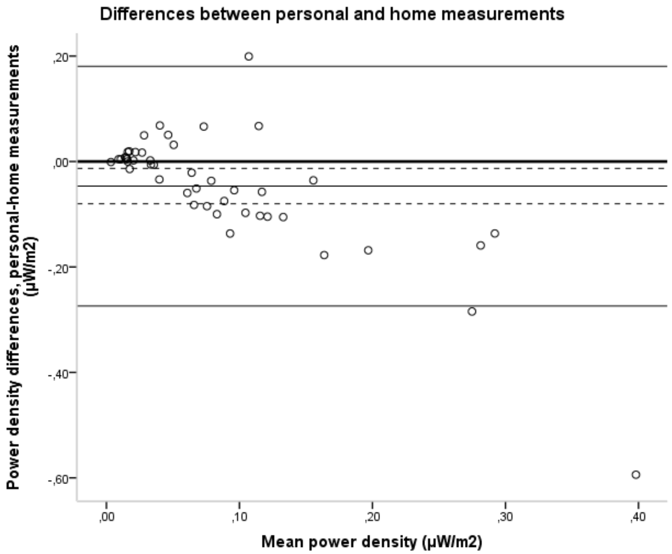
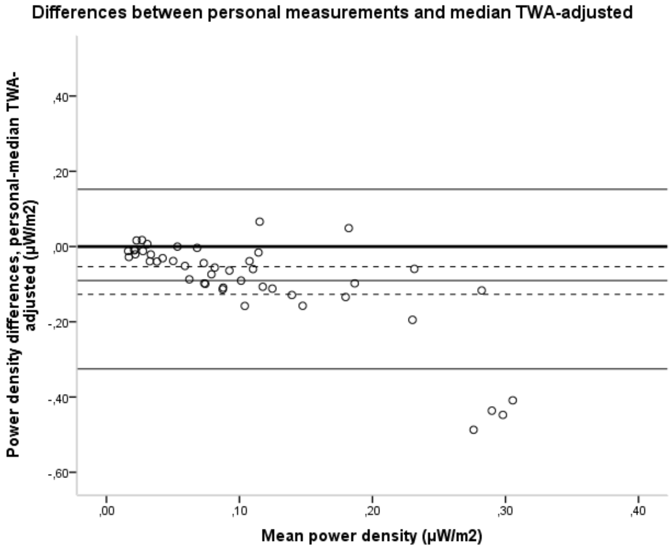
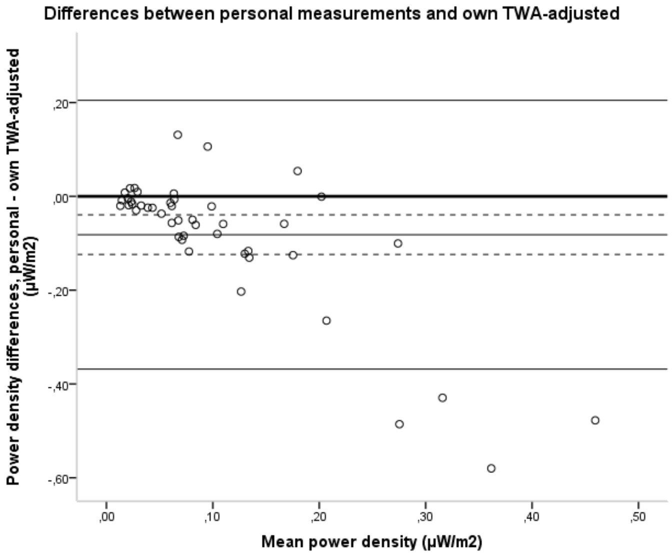


Figure 1: Contribution of different sources to total RF exposure


Differences between personal and home measurements
Power density differences, personal-home measurements (µW/m2)
,20
,00
-,20
-,40
-,60
,00
,10
,20
,30
,40
Mean power density (µW/m2)


Differences between personal measurements and median TWA-adjusted
Power density differences, personal-median TWA-adjusted (µW/m2)
,40
,20
,00
-,20
-,40
-,60
,00
,10
,20
,30
,40
Mean power density (µW/m2)


Differences between personal measurements and own TWA-adjusted
Power density differences, personal - own TWA-adjusted (µW/m2)
,20
,00
-,20
-,40
-,60
,00
,10
,20
,30
,40
,50
Mean power density (µW/m2)

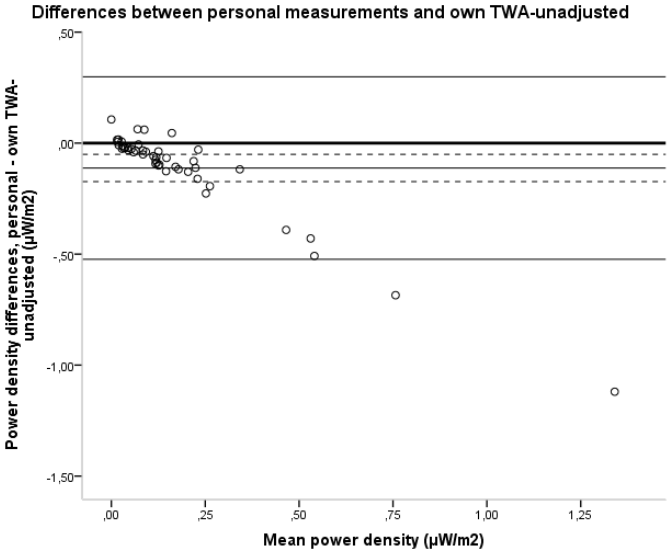

Differences between personal measurements and own TWA-unadjusted
Power density differences, personal - own TWA-unadjusted (µW/m2)
,50
,00
-,50
-1,00
-1,50
,00
,25
,50
,75
1,00
1,25
Mean power density (µW/m2)

Figure 2: Bland-Altman plots of the mean RF levels. Vertical axes represent power density differences between personal measurement and each of the approaches based on spot measurements; horizontal axes represent mean power density of personal measurement and each of the approaches based on spot measurements; the solid bold line represents the difference zero between the two methods studied; the other solid lines represent the mean difference and mean difference ± 1.96 standard deviations; the dashed lines represent the confidence interval (95%) of the mean difference; The bias between the two methods is represented by the gap between the solid bold line and the mean difference line (solid non-bold line); two children were excluded since they were extreme outliers and made it difficult to plot the graphs.