Temporal trends of radio-frequency electromagnetic field (RF-EMF) exposure in everyday environments across European cities

Damiano Urbinello[1,2,3]*, Wout Joseph*[3]*, Leen Verlock*[3]*, Luc Martens*[3] *and Martin Röösli*[1,2]

[1]Swiss Tropical and Public Health Institute, Department of Epidemiology and Public Health Socinstrasse 57, CH-4002 Basel

[2]University of Basel, Basel, Switzerland

[3]Department of Information Technology, Ghent University / iMinds Gaston Crommenlaan 8, B-9050 Ghent, Belgium

Correspondence to: Martin Röösli, Swiss Tropical and Public Health Institute, Department of Epidemiology and Public Health, University of Basel, Socinstrasse 57, Basel, CH-4002, Switzerland.

Phone: +41 61 284 83 83, Fax: +41 61 284 85 01, e-mail: martin.roosli@unibas.ch

ABSTRACT

Background

The rapid development and increased use of wireless telecommunication technologies led to a substantial change of radio-frequency electromagnetic field (RF-EMF) exposure in the general population but little is known about temporal trends of RF-EMF in our everyday environment.

Objectives

The objective of our study is to evaluate temporal trends of RF-EMF exposure levels in different microenvironments of three European cities using a common measurement protocol.

Methods

We performed measurements in the cities of Basel (Switzerland), Ghent and Brussels (Belgium) during one year, between May 2011 and April 2012. RF-EMF exposure in 11 different frequency bands ranging from FM (Frequency modulation, 88 MHz) to WLAN (Wireless Local Area Network, 2.5 GHz) were quantified with portable measurement devices (exposimeters) in various microenvironments: outdoor areas (residential areas, downtown and suburb), public transports (train, bus and tram or metro rides) and indoor places (airport, railway station and shopping centers). Measurements were collected every four seconds during 10 to 50 minutes per environment and measurement day. Linear temporal trends were analyzed by mixed linear regression models.

Results

Highest total RF-EMF exposure levels occurred in public transports (all public transports combined) with arithmetic mean values of 0.84 V/m in Brussels, 0.72 V/m in Ghent, and 0.59 V/m in Basel. In all outdoor areas combined, mean exposure levels were 0.41 V/m in Brussels, 0.31 V/m in Ghent and 0.26 V/m in Basel.

Within one year, total RF-EMF exposure levels in all outdoor areas combined increased by 57.1% ($p<0.001$) in Basel by 20.1% in Ghent ($p=0.053$) and by 38.2% ($p=0.012$) in Brussels Exposure increase was most consistently observed in outdoor areas due to emissions from mobile phone base stations. . In public transports RF-EMF levels tended also to increase but mostly without statistical significance.

Discussion

An increase of RF-EMF exposure levels has been observed between April 2011 and March 2012 in various microenvironments of three European cities. Nevertheless, exposure levels were still far below regulatory limits of each country. A continuous monitoring is needed to

identify high exposure areas and to anticipate critical development of RF-EMF exposure at public places.

KEYWORDS

Radio-frequency electromagnetic fields (RF-EMF), temporal trends, personal exposure, monitoring, exposimeter

1. INTRODUCTION

The introduction and development of new wireless telecommunication technologies led to a substantial change of radio-frequency electromagnetic field (RF-EMF) exposure patterns.

To meet technological requirements and advantages of newly launched wireless devices, the telecommunication network has to be expanded and optimized. The use of new mobile technologies has increased and is still further augmenting, whereas transmission of data through the mobile internet became more efficient resulting in lower RF-EMF emissions per transmitted byte of data. At this point, it is unclear what the net effect on exposure level is and whether exposure is increasing in everyday environments over time.

In the last few years, several measurement studies have been conducted characterizing RF-EMF exposure levels in different microenvironments and comparing exposure in different cities using personal exposimeters (Berg-Beckhoff et al., 2009; Bolte and Eikelboom, 2012; Frei et al., 2009; Joseph et al., 2010; Joseph et al., 2008; Thuróczy et al., 2008; Viel et al., 2009). These studies found that RF-EMF levels in the everyday environment are far below the regulatory limits. Several studies examined short-term temporal variability of RF-EMF exposure during one day (Mahfouz et al., 2011; Mahfouz et al., 2013; Manassas et al., 2012; Miclaus et al., 2013) or up to one week (Joseph and Verloock, 2010; Joseph et al., 2009; Vermeeren et al., 2013) addressing variation between daytime and nighttime or during weekdays and weekends (Joseph et al., 2009). However, studies evaluating temporal trends over longer time periods as one year are lacking so far. Frei et al. (2009) stated that introduction of mobile phone technology has resulted in a 10-fold increase of RF-EMF at outdoor areas compared to the time period before when broadcast transmitting was the most relevant source (Frei et al., 2010; Mohler et al., 2012).

To be reliable, such a temporal trend analysis needs a substantial amount of data from different environments that are collected with the same methodology (Joseph et al., 2010). Repeated measurements with portable measurement devices in various microenvironments allow to efficiently collect a high number of measurements per microenvironment (Röösli et al., 2010).

The aim of this microenvironmental measurement study was to characterize RF-EMF exposure levels in typical everyday environments and to investigate temporal trends in outdoor areas, public transports, and indoor settings of three different European cities.

2. METHODS

Data collection took place in Basel (Switzerland), Ghent and Brussels (Belgium) between April 2011 and March 2012. All measurements are based on a common measurement protocol adopted in each city in order to enable direct comparisons.

2.1. Definition of microenvironments and measurement procedures in the different cities

We included characteristic everyday environments in outdoor areas, where measurements occurred exclusively outside buildings in free space, public transports (train, bus, tram and metro) and indoor settings (2 different shopping centers per city, main railway station of each city and the airport of Basel and Brussels) in our study areas (Table 1). Measurements in outdoor areas include central- and non-central residential areas, downtown areas and suburban areas. Areas were matched across cities according to several criteria: central residential areas are located in zones with higher buildings (4-5 floors) and more traffic as well as more people on sidewalks. Non-central residential areas are, in contrast, situated outside the city center in quiet residential zones with building heights up to 3 floors and relatively large parts of green space compared to central residential and downtown areas. Downtown areas represent the city center with busy pedestrian zones. Data was further collected in public transports such as express trains (train rides included measurements between Aarau and Basel (Switzerland), Ghent and Brussels (Belgium), buses (bus rides in each city between the suburban area and the inner city), trams (various tram rides within the city) and metro (only within the city of Brussels, as there are no trams). Indoor settings included Basel's and Brussels' airport, railway stations in Basel (Basel main station), Ghent (Ghent-Sint-Pieters main station) and Brussels (Central station – Gare Centrale) and shopping centers (two major shopping malls per city).

Measurements were conducted once every month during one year. Data were collected by the same research assistant each time, by walking along the same routes using the same time schedules each month.

In Basel, data were collected in the first week of each month on Wednesdays and Thursdays in the morning between 7:30 and 11:40. In Ghent and Brussels, measurements were conducted in the third week of each month, on Wednesdays in Ghent (including measurements at Brussel's airport), between 8:45 and 16:45 and on Thursdays in Brussels, between 8:40 and 17:40 (see Table 1). Measurements were shifted by one week in case data collection could not be performed in the first and third week, respectively. The exposimeter was carried on the rear of the body in a bag. The exposimeter was fixed in the bag and placed vertically. During measurements in public transports, the bag was placed either in front of the study assistant or next to him on a free seat when seating (typically in trains, buses and metros) or on the rear of the body if the assistant had to stand (usually in trams). In the latter case, an attempt was made to have no persons in close vicinity. Measurement duration in the same microenvironment was always the same and ranged between 10 to 60 minutes for different environments (Table 1). For this duration of measurements within a microenvironment we have previously observed to produce reproducible and reliable results in the sense that average exposures within a type of microenvironment approach a stable mean value (Beekhuizen et al., 2013; Urbinello et al., 2014). The mobile phone was turned off during data collection. All measurements occurred during daytime.

2.2. *Study instruments*

We performed our measurements using an exposimeter of the type EME Spy 120 from SATIMO (SATIMO, Courtaboeuf, France, http://www.satimo.fr/), capable to quantify personal RF-EMF exposure on 12 different frequency bands: frequency modulation (FM, 88-108 MHz); television (TV, 174-223 MHz and 470-830 MHz); Terrestrial Trunked Radio (TETRA, 380-400 MHz); Global System for Mobile Communications at 900 MHz downlink (i.e., communication from base station to mobile phone, 925-960 MHz) and uplink (i.e., communication from mobile phone to base station, 880-915 MHz), GSM at 1800 MHz (GSM1800) downlink (1805-1880 MHz) and uplink (1710-1785 MHz); Digital Enhanced Cordless Telecommunications (DECT, 1880-1900 MHz); Universal Mobile Telecommunications System (UMTS) downlink (2110-2170 MHz) and uplink (1920-1980 MHz) and Wireless Local Area Networks (WLAN, 2400-2500 MHz). The exposimeter has a lower detection limit of 0.0067 mW/m^2 (corresponding to 0.05 V/m of electric field strength) and an upper detection limit of 66.3 mW/m^2 (5 V/m). The measurement interval was configured to 4 seconds in order to collect a maximal number of data points, generating robust datasets. An application on a smartphone was developed from the Swiss Federal Institute of Technology (ETH Zurich) which allowed recording the time by clicking on start and stop when beginning and finishing the measurements in a microenvironment, respectively. The smartphone was in flight modus while doing the measurements preventing exposure contribution from the own mobile handset. The device was calibrated in October 2010, April 2011, and December 2011 at the ETH Zurich showing temporal fairly stable calibration factors. However, although GSM 1800 downlink and UMTS uplink were correctly detected by the exposimeter, we observed that the presence of these bands affected the DECT measurements (cross-talk). Since the presence of DECT fields is negligible in outdoor areas and public transports (no cordless phones) we omitted this frequency range. DECT is also of minor importance in indoor settings we included, i.e. shopping centers, airport and train station. Our results are still comparable with other studies that have DECT included in such microenvironments. On the other hand, the calibration revealed that DECT signals were also taken up in the UMTS uplink frequency band. However, since little DECT was present in our study area, this does not result in a bias.

2.3. Statistical analyses

To take into account that a large proportion of data points were below the lower detection limit of the exposimeter, arithmetic mean values have been calculated for each measurement day per frequency and per environment with the robust regression on order statistics (ROS) algorithm using the statistical software R Version 3.0.1 (www.r-project.org) (Röösli et al., 2008). A full description of the analysis method can be found in Helsel (2005). All calculations were made on power flux density levels ($\mu W/cm^2$) and then back-transformed to electric field strength (V/m). Annual mean values per microenvironment were obtained by averaging these daily mean values. For the analyses we considered three relevant frequency groups: i) total RF-EMF exposure: sum of mean power flux densities of all frequency bands apart from DECT (Digital Enhanced Cordless Telecommunications). We excluded DECT, since calibration showed cross-talk with nearby bands, i.e. GSM1800; ii) mobile phone base station exposure: sum of mean power flux densities of all downlink frequencies (GSM900 (925-960 MHz), GSM1800 (1805-1880 MHz) and UMTS (2110-2170 MHz)); and iii) mobile phone handset exposure: sum of mean power flux densities of all uplink frequencies (GSM900 (880-915 MHz), GSM1800 (1710-1785 MHz) and UMTS (1920-1980 MHz)).

Temporal trends were examined using linear regression models. Month as integer was introduced as linear term in the models. To achieve normally distributed residuals, all calculations were done on the log-transformed power flux density scale and model coefficients were back-transformed thus reflecting annual changes of the geometric mean value on the electric field scale (V/m). Trend analyses of combined microenvironments (all outdoor areas and all public transports combined) were based on multilevel mixed-effects models with type of microenvironment as cluster variable. Trend analyses of single microenvironments were conducted using log-linear regressions. Analyses were conducted with STATA version 12.1 (StataCorp, College Station, TX, USA).

3. Results

3.1. Characterization of RF-EMF exposure levels in different environments

Table 2 summarizes RF-EMF exposure levels for the different environments (outdoor areas, public transports and indoor settings) across all three cities.

Highest total RF-EMF exposure levels occurred in all public transports combined. In trains exposure levels ranged between 0.83 V/m (Ghent) and 1.06 V/m (Brussels) and were considerably higher compared to other environments (Table 2a). Mobile phone handsets were the main exposure source in trains (Table 2c, Online Figure 1b), whereas in other public transports, such as buses and trams or metros, mobile phone base stations have also a considerable impact on the exposure situation (Table 2b).

RF-EMF exposure is highly spatially variable (Table 2a and 2b) across different outdoor areas within one city. Highest total RF-EMF exposure occurred in downtown areas (Basel: 0.49 V/m, Brussels: 0.58 V/m) and in one central residential area (Ghent: 0.42 V/m). In contrast, lowest values were observed in a central (Basel: 0.16 V/m) and non-central residential areas (Ghent: 0.17 V/m; Brussels: 0.24 V/m). In outdoor areas, highest contribution to total RF-EMF exposure originates from mobile phone base stations (Table 2b), whereas mobile phone handset exposure was negligible in outdoor areas of Basel and Ghent (<0.11 V/m), but seems to play a more important role in several areas of Brussels (Table 2c).

Exposure situation at the airport was highest compared to other indoor settings. Total RF-EMF exposure was highest at the railway station (0.57 V/m, Brussels) and at the airport: 0.53 V/m (Brussels) and 0.54 V/m (Basel) (Table 2a). In indoor settings, both, mobile phone base stations and handsets contributed a fair amount to total RF-EMF exposure (Table 2b and 2c).

3.2. Temporal trends

We observed a considerable change in RF-EMF exposure situation during the period between April 2011 and March 2012 across all cities.

Figure 1a and 1b suggest a consistent increase of RF-EMF exposure in urban outdoor areas considering total RF-EMF and mobile phone base station exposure, which is the most relevant source in outdoor areas. Trend analysis using multilevel mixed effects linear models support the graphical facts (Figure 1b) with highly statistically significant increases in geometric mean of mobile phone base station exposure for all outdoor areas combined in Basel (64.0%, p<0.001), Ghent (23.6%, p=0.021) and Brussels (68.3%, p<0.001) (Table 2b). Area-specific yearly changes were also more pronounced in the Basel outdoor areas than in the corresponding areas of Ghent. In Brussels, area specific trends were heterogeneous ranging from a 26.4% increase (p=0.377) in the downtown area to a 120.2% (p=0.002) increase in the central residential area (Table 2b). Temporal increase of mobile phone handset exposure reached statistical significance at only few outdoor areas (central residential areas of Basel and Ghent as well as non-central residential area in Brussels) (Table 2c).

In public transports, RF-EMF exposure is highly variable as shown in Figure 2a-c. Mobile phone handset exposure is the most relevant source in public transports, especially in trains. Total RF-EMF tended to increase in most public transport settings but did not reach statistically significance for all public transports combined in any of the cities (Table 2a). Statistically significant trends for mobile phone handset exposure were only observed in metros in Brussels (117.3%, p=0.028) (Table 2c).

In indoor settings, total RF-EMF exposure increased significantly at the airport (64.3%, p=0.032) and shopping centers (100.7%, p=0.005) in Basel (Table 2a) but not at corresponding areas in Ghent and Brussels. Interestingly, across all indoor areas in all cities, mobile phone base station exposure showed a stronger temporal increase than mobile phone handset exposure (Table 2b and 2c). At the airport of Brussels even a significant decrease of handset exposure was observed (Table 2c).

4. Discussion

Our study offers a comparison and time trend analysis of RF-EMF exposure levels collected during one year in typical everyday microenvironments (outdoor areas, public transports and indoor settings) across three European cities. For outdoor areas we found a significant temporal increase of RF-EMF exposure levels. In public transports exposure levels were higher than in outdoor areas and showed a larger day to day variation and temporal increase did not reach statistical significance.

4.1. Interpretation

Overall, our study gives strong indications that, especially mobile phone base station exposure at outdoor areas increased over the study period between April 2011 and March 2012. At outdoor areas temporal increase was higher in Basel's area compared to Belgium. This may be due to the difference in increased coverage and capacity demands. A further explanation may be that the introduction of precautionary limits in Belgium, which came in effect in 2009 in Brussels (Ordinance of the Brussels Capital Region of 14 March 2007) and in 2011 in Ghent (Ordinance of the Flemish Region of Nov. 2010) and thus was still in the adaption process during the measurement period, which could have slowed down the exposure increase, where precautionary limits in Switzerland are established since 2001 (ONIR, 1999).

Interestingly, highest exposure levels occurred consistently in trains across all cities with distinct contribution from mobile phone handsets. This has several reasons: the inner space of a train can be considered as Faraday cage, reflecting emitted radiation by mobile phones. Additionally, the density of people using their mobile phones' is usually higher in trains than in other environments. Nowadays, mobile phones are not only used for messaging and calls anymore but rather also for using a large variety of web-based applications (apps), such as news alerts, e-mails, mobile television and many other apps, increasing the use of mobile phone handsets during train rides resulting in higher uplink exposure levels. Moreover, location updates or handovers are executed when moving around in order to maintain constant connectivity to the mobile phone base station of the respective area when the device is in stand-by mode or during a call, respectively (Urbinello and Röösli, 2013). These aspects are also relevant for the exposure situation in buses, trams and metros but in these environments we have mainly measured outside the commuting rush hours (see table 1) with a lower passenger density compared to trains.

The impact of the communication infrastructure on the exposure situation can be exemplarily highlighted by comparing measurements in trams and metros. Total mobile phone handset exposure was considerably higher in metros vs. trams (0.67 V/m vs. 0.21 and 0.41 in trams in Basel and Ghent), whereas mobile phone base station exposure was lower in the metro than in trams (0.16 V/m vs. 0.23 and 0.27 V/m). Metros are running underground and in underground stations micro- and pico cells are installed. Furthermore, the coverage in metros may be poor, so that the mobile devices have to emit with stronger signals.

We have hypothesized that increase of exposure levels would be most pronounced in public transports, because of a strong increase in internet use with mobile phones after the introduction of smart phones. However, this was not the case. Over all public transports combined, temporal trends did not reach statistical significance in all three cities. Lack of significance is partly explained by the higher data variability from handset exposure, which has resulted in larger confidence intervals. The lower increase on the relative scale is probably the consequence of higher exposure levels in public transports. Thus, the increase on the absolute scale is actually higher for many public transports compared to outdoor areas. For instance the observed (significant) 63.7% increase in geometric mean in the central residential area of Basel corresponds to an increase of 0.16 V/m whereas the (non-significant) 39% increase in trains in Brussels corresponds to 1.01 V/m. A further issue which may appear contradictory is the increase of exposure from mobile phone base stations and a decrease of exposure from mobile phone handsets at the airport since there is an interaction between up- and downlink exposure. However, this interaction is complex and it has been demonstrated that the higher the exposure levels from the base station, the lower is the output power of mobile phones (Yuanyuan et al., 2014; Aerts et al., 2014). Further, one has to be aware that RF-EMF exposure decreases rapidly with increasing distance and thus, walking through a waiting hall at the airport will not capture uplink exposure from all emitting mobile devices in the considered area.

It is difficult to predict how RF-EMF exposure will further change over time. Assuming a linear trend of increase in RF-EMF exposure, it might be reasonable to argue that exposure will exceed regulatory limits somewhere in the future. However, along with the increase of new telecommunication devices, technologies became also more efficient in reducing emission characteristics of mobile phones. Our results suggest that the increase in number and amount of mobile phone users has not been compensated with more efficient technologies and the net effect is an increase in exposure levels for most microenvironments. Also the output power of mobile phones is affected by the technology. For example second generation mobile phones (2G, GSM) use a power control, radiating with full intensity during connection establishment and down-regulate as soon as a call has been established (Lönn et al., 2004). Smartphones of the third generation (3G, UMTS) in contrast, have a so-called enhanced adaptive power control which optimizes radiation according to the quality of connectivity to the mobile phone base station, resulting in considerable lower average output power (Gati et al., 2009; Persson et al., 2011; Wiart et al., 2000), which may also affect overall RF-EMF exposure.

4.2. Comparison of RF-EMF exposure levels with the literature

In previous studies, RF-EMF measurements had primarily been collected through volunteers, who filled in an activity diary and carried a measurement device during their typical daily activities. Since the volunteers were usually not asked to restrict their mobile phone use during the study (Frei et al., 2009), this affects personal measurements during a call (if not omitted from the data analysis) but also in stand-by mode because of organizational communication (Urbinello and Röösli, 2013), which cannot be identified in the measurement file. If diary data were not entirely accurate in volunteer studies measurements may be assigned to the wrong microenvironment in such studies. Nevertheless, we found similar results in outdoor urban environments as in a previous study conducted by Joseph et al. (2010); which reported total RF-EMF exposure levels of 0.28 V/m for Switzerland (our study - Basel: 0.26 V/m) and 0.37 V/m for Belgium (our study – Ghent: 0.31 V/m, Brussels: 0.41 V/m). Exposure in trains were higher in our study (0.97 V/m in Basel, 0.83 V/m in Ghent and 1.06 V/m in Brussels) compared to the previous study: 0.63 V/m (Switzerland) and 0.59 V/m (Belgium).

In a recent study conducted by Bolte and Eikelboom (2012) in the Netherlands with 98 volunteers carrying a personal measurement device during their typical daily activities, similar total RF-EMF exposure values were reported for shopping centers (NL: 0.29 V/m vs. Basel: 0.22 V/m, Ghent: 0.32 V/m, Brussels: 0.37 V/m), outdoor areas (0.30 V/m compared to 0.26 V/m, 0.31 V/m and 0.41 V/m), railway stations (0.35 V/m vs. 0.34 V/m, 0.32 V/m and 0.57 V/m) and buses (0.29 V/m vs. 0.35 V/m, 0.36 V/m and 0.37 V/m). However, total RF-EMF exposure in trains was considerably lower in the Netherlands than in the present study (0.37 V/m vs. 0.97 V/m, 0.83 V/m and 1.06 V/m). In trams and metros, exposure levels were similar in the Netherlands (0.34 V/m) and in Basel (0.32 V/m) but higher in Ghent (0.50 V/m) and Brussels (0.70 V/m).

Note that all these previous studies included also DECT (Digital Enhanced Cordless Telecommunication) frequency when calculating total RF-EMF exposure, which is, not the case in our study. However, DECT cordless phone exposure is not expected to be relevant for RF-EMF exposure in outdoor and train environments, but rather more in environments like in households or in offices where people spend most of their time.

4.3. *Comparison of temporal trends with the literature*

The number of studies examining temporal trends based on personal measurements on a larger time scale up to one year is very limited. A study performed in Lower Austria examined spot measurements with a spectrum analyzer during daytime in bedrooms in 2006 and a follow-up investigation in 130 identical homes was performed in 2009 (Tomitsch and Dechant, 2012). The authors concluded from their results, that median RF-EMF exposure in bedrooms increased from 41.35 μW/m^2 (0.12 V/m) to 59.56 μW/m^2 (0.15 V/m). Median exposure from mobile phone base stations has increased by a factor 2 during these three years (from 7.68 to 15.12 μW/m^2). This study differed to our research in terms of microenvironments, as we did not measure in households, and equipment (spectrum analyzer vs. exposimeter). In contrast a large survey of mobile phone base station measurements from the US, UK, Spain, Greece and Ireland did not indicate an increase in mobile phone downlink exposure between the years 2000 and 2009 (Rowley and Joyner 2012). The European narrowband measurements originated from monitoring sites close to mobile phone base stations on ground-base, whereas the US broadband measurements included many rooftops and other locations around base stations. The dataset of this publication is impressive but it is unclear whether temporal trends are affected by the underlying heterogeneous dataset, whereas our study used the exact same procedure over the entire study period. Monitoring systems have been implemented in various cities in Europe, such as in Greece (Gotsis et al., 2008), Italy (Troisi et al., 2008) and Portugal (Oliveira et al., 2007). However, no analyses of time trends are available from these measurement networks. In Basel, prior to this study, measurements have been already collected every month between May 2010 and 2011 in the very same microenvironments (Röösli et al., submitted). Time trend analyses for the entire 2-year period yielded annual increases ranging from 14% for downtown area up to 32% in central residential areas.

4.4. Strengths and limitations

A strength of the study is the use of a common measurement protocol in all three cities of Basel, Ghent, and Brussels. In previous studies, comparison of results between countries was limited due to different study designs: i.e. different applied methodologies, such as recruitment strategies of study participants, different data collection procedures and different methods of data analysis (Joseph et al., 2010). In present study, the same study assistant collected measurements in all cities and performed all analysis ensuring accurate assignment measurements to microenvironment which may not be the case in volunteer study. The mobile phone was switched off during data collection avoiding influences from the own mobile phone to personal measurements which can result in an overestimation of personal exposure, as it impacts personal measurements which was shown in Urbinello and Röösli (2013). In addition, the study design applying repetitive standardized measurements on a monthly basis, at the same days and times, enabled to draw conclusions about temporal variations, for the first time during an entire year.

Our study has also limitations; since we just considered two working days and performed measurements during daytime, we have not taken into account temporal exposure trends during night or weekends. However, difference in exposure has been found to be low between different days of the week (Beekhuizen et al., 2013; Joseph and Verloock, 2010; Joseph et al., 2009). Exposure from mobile phone base stations seems to be slightly higher during weekdays than weekend (Joseph et al., 2009, Mahfouz et al., 2013) and electric field strength was found to be about 10-30 percent higher during daytime than during nighttime (Manassas et al., 2012, Mahfouz et al., 2011), indicating some overestimation of the average exposure situation.

Measurement duration in some of the microenvironments was relatively low (e.g. non-central residential area). This is not expected to bias the trend analysis, because this measurement protocol has been shown to provide reproducible values (Beekhuizen et al., 2013). However, the reported values may not be fully representative for the whole corresponding measurement area. The higher the spatial variability the less representative values may be obtained with a short measurement duration. Thus, uplink exposure in all areas and downlink exposure in non-central residential areas with a low transmitter density are mostly affected. In order to address the representativity of our findings on a larger geographic scale we suggest applying our measurement protocol for at least 20 minutes or longer in additional microenvironments.

On the other hand, the exposimeter was carried close to the body in a bag, thus shielding of the human body is expected to have influenced our results to some extent, as shielding of the body is expected to lead to underestimation of personal RF-EMF exposure (Bolte et al., 2011; Iskra et al., 2010; Neubauer et al., 2008; Thielens et al., 2013). Resulting extent of underestimation depends on the frequency band. For the GSM900 downlink band correction factors between 1.1 and 1.3 and for UMTS downlink and W-LAN correction factors of 1.1 to 1.6 have been suggested (Bolte et al., 2011; Neubauer et al., 2010). Bolte et al., 2011 did a comprehensive uncertainty analysis for personal EME SPY 121 measurements addressing in addition to body shielding calibration and elevation arrival angle. To take all of these uncertainties in count, they propose frequency band specific correction factors between 1.1 and 1.6. Thus, the level of exposure may be somewhat underestimated, however, this bias is unlikely to have affected temporal trend analysis. We have only measured a limited number of microenvironments and thus, the generalizability of the observed trends in these microenvironments for all other environments from the same type in Belgium and Switzerland is somewhat uncertain. In terms of population exposure it would be interesting to extent this study to the work place and homes, where people spend most of their time. However, such a study would be very costly.

5. Conclusions

Our study offers for the first time a diligent comparison of temporal trends during a year between countries as it based on a common measurement protocol applied in all cities. We could consistently demonstrate that all exposure levels were far below reference levels proposed by ICNIRP (International Commission on Non-Ionizing Radiation Protection). Exposure levels were of the same order of magnitude in all cities. Consistently in all cities, exposure was highest in public transports (train) and lowest in residential areas (central and non-central residential areas). We found substantial increase of exposure levels for most microenvironments. It is crucial to further monitor the exposure situation in different environments in order to examine if and how exposure changes over time and to anticipate critical areas.

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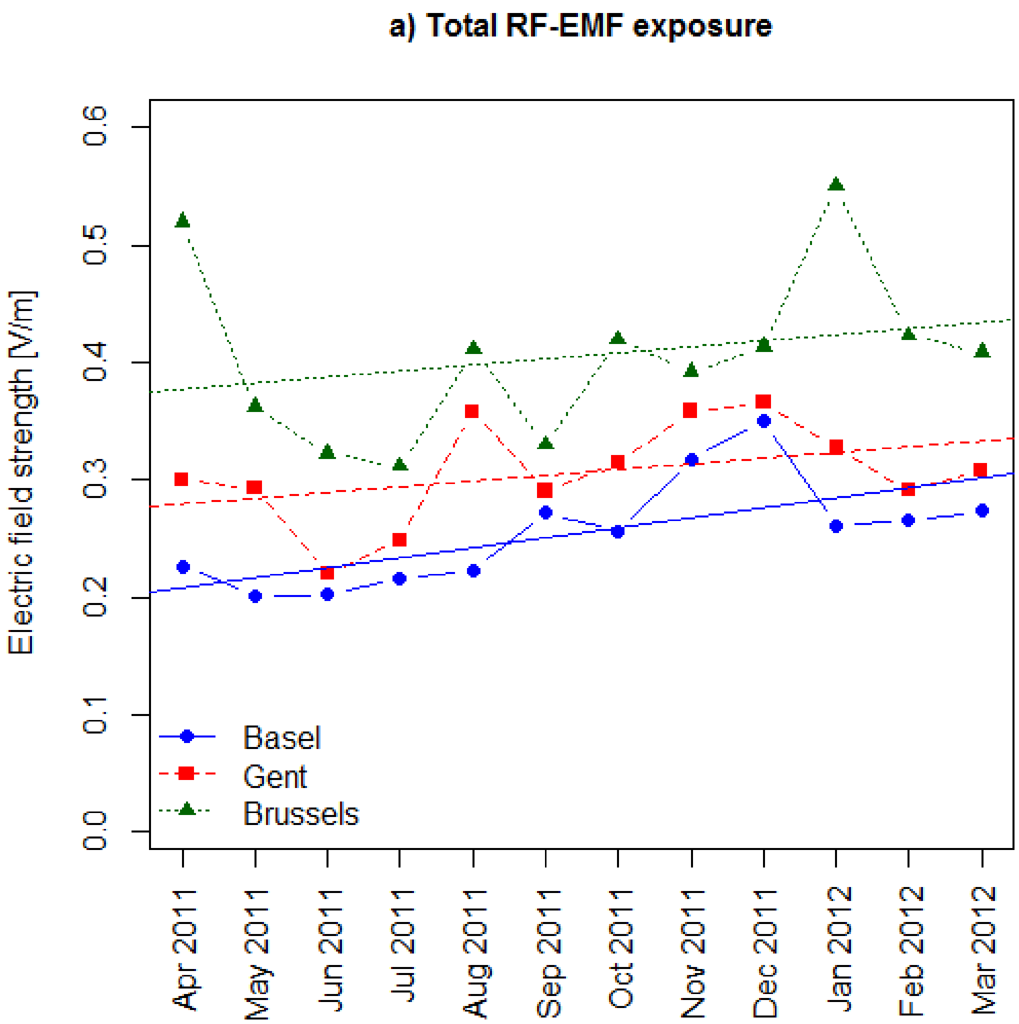
Conflict of interest

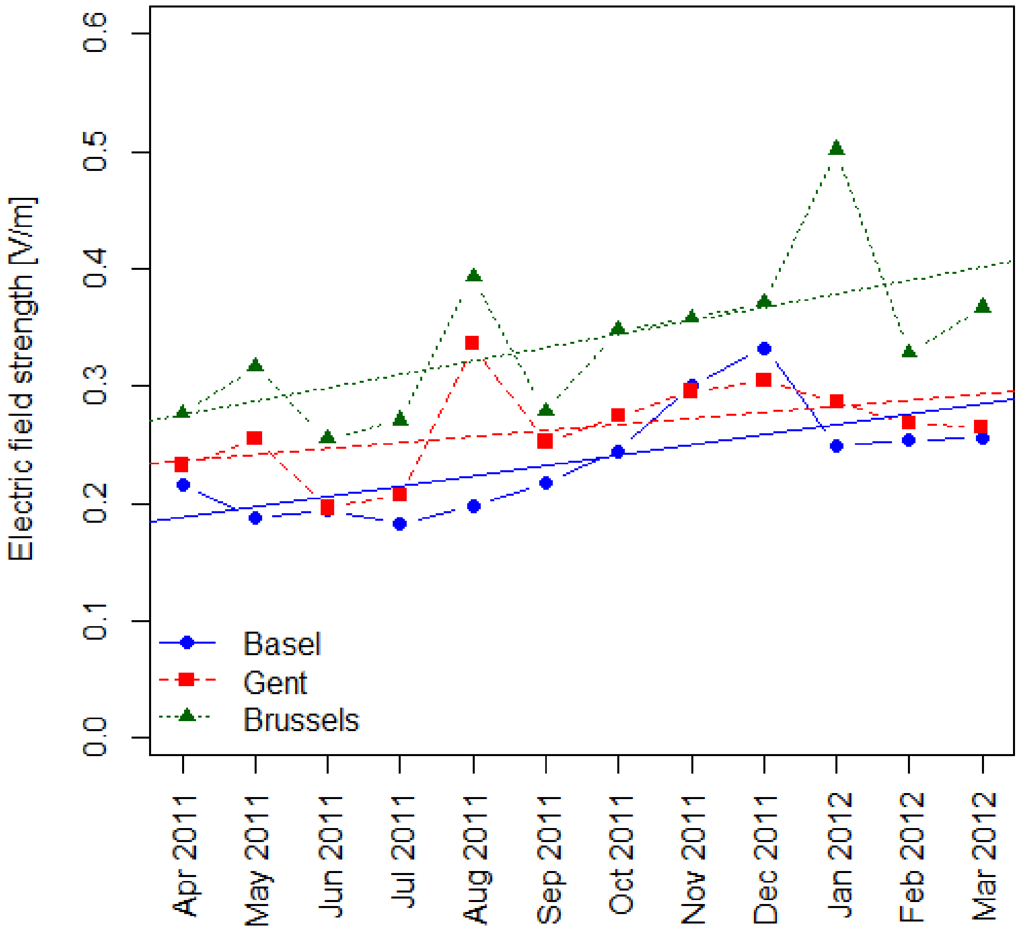
The authors declare no conflict of interest.

FIGURES

Figure 1. Monthly average RF-EMF exposure levels for all outdoor areas combined between April 2011 and March 2012 for total RF-EMF (a), mobile phone base station (b) and mobile phone handset exposure (c).



b) Mobile phone base station exposure



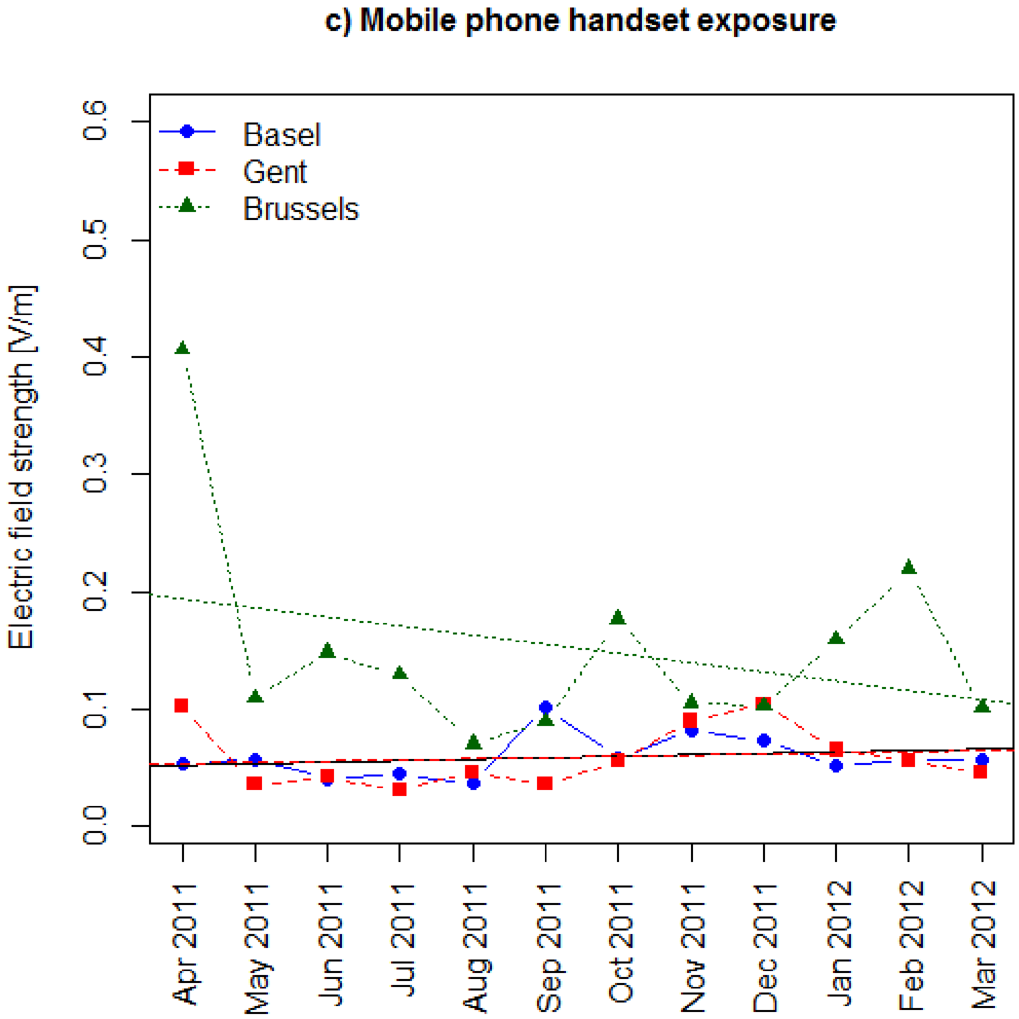
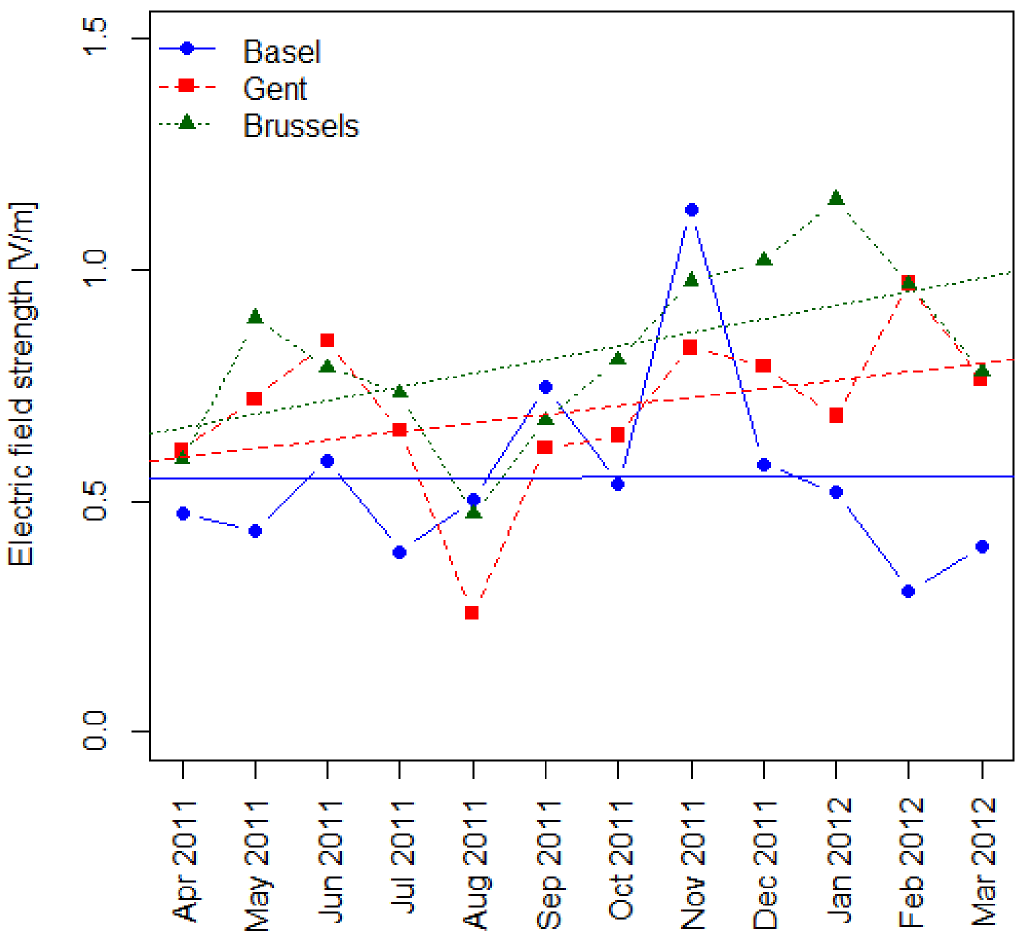
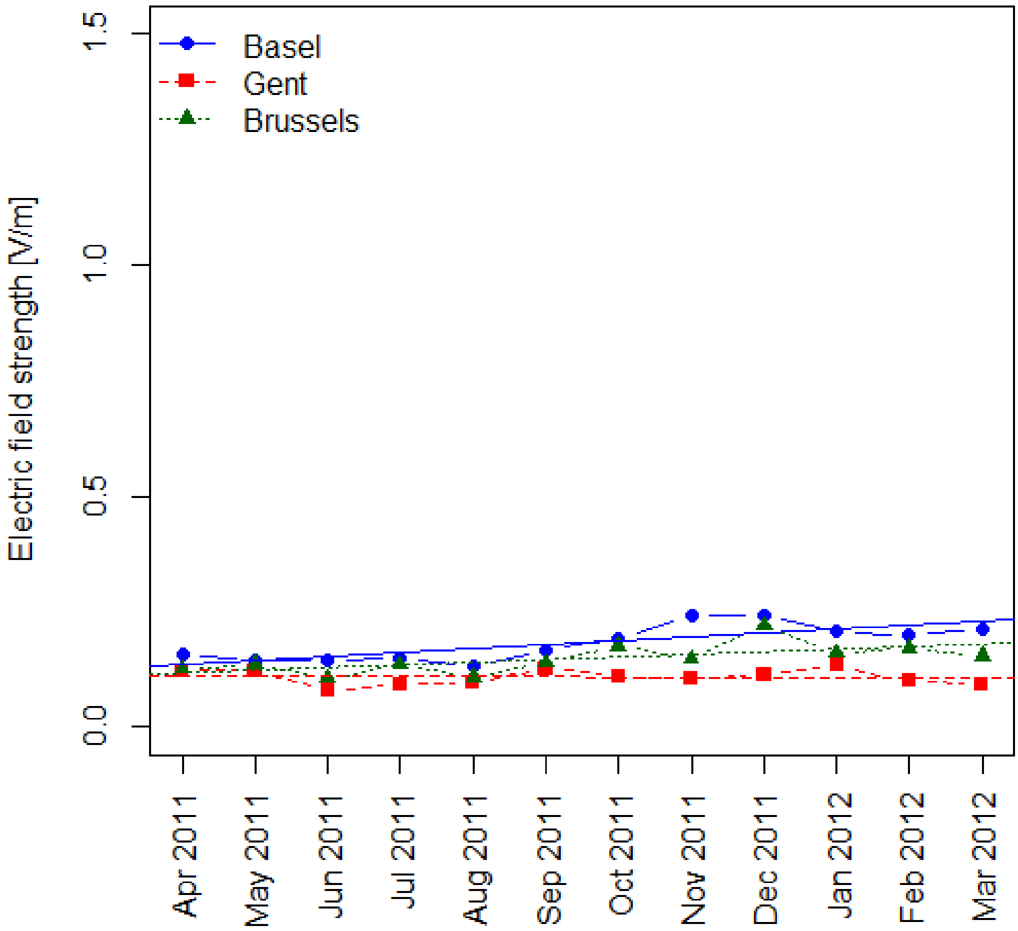


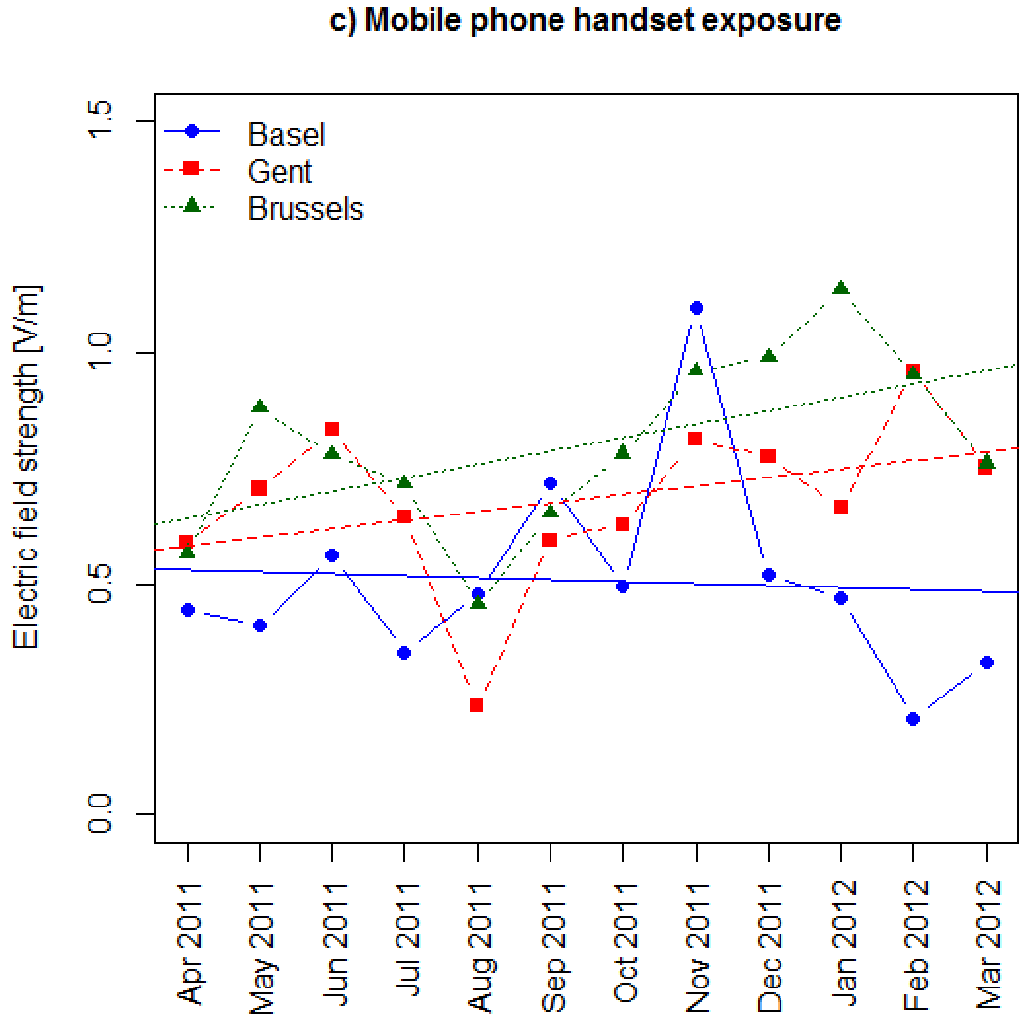
Figure 2. Monthly average RF-EMF exposure levels for all public transports combined between April 2011 and March 2012 for total RF-EMF (a), mobile phone base station (b) and mobile phone handset exposure (c).

a) Total RF-EMF exposure

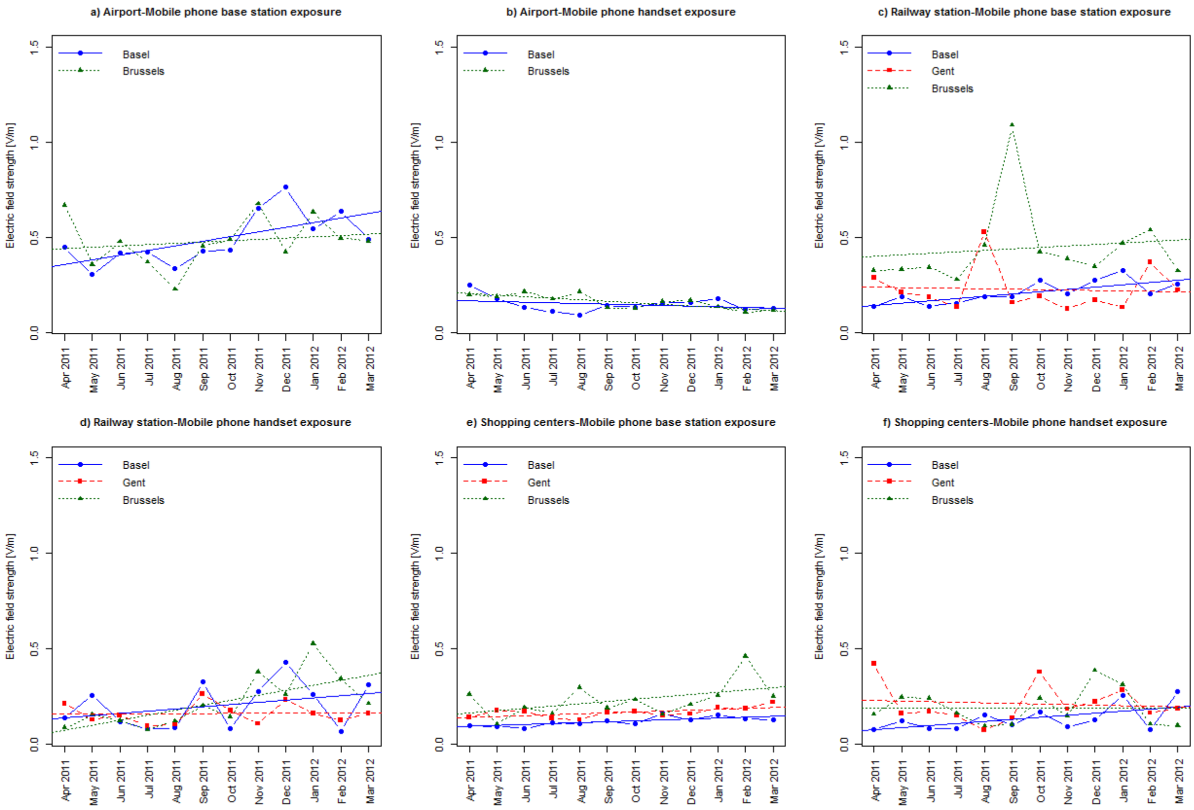


b) Mobile phone base station exposure





Online Figure. Monthly average RF-EMF exposure levels for indoor settings between April 2011 and March 2012 for mobile phone base station (a) and mobile phone handset exposure (b).


a) Airport-Mobile phone base station exposure
b) Airport-Mobile phone handset exposure
c) Railway station-Mobile phone base station exposure
d) Railway station-Mobile phone handset exposure
e) Shopping centers-Mobile phone base station exposure
f) Shopping centers-Mobile phone handset exposure
Basel
Gent
Brussels
Electric field strength [V/m]
0.0
0.5
1.0
1.5
Apr 2011
May 2011
Jun 2011
Jul 2011
Aug 2011
Sep 2011
Oct 2011
Nov 2011
Dec 2011
Jan 2012
Feb 2012
Mar 2012