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Measuring personal exposure from 900 MHz mobile phone base stations in Australia and Belgium using a novel personal distributed exposimeter

Chhavi Raj Bhatt [a,*], Arno Thielens [b], Mary Redmayne [a], Michael J. Abramson [a], Baki Billah [c], Malcolm R. Sim [a], Roel Vermeulen [d,e,f], Luc Martens [b], Wout Joseph [b], Geza Benke [a]

[a] Centre for Population Health Research on Electromagnetic Energy (PRESEE), School of Public Health and Preventive Medicine, Monash University, The Alfred Centre, 99 Commercial Road, Victoria 3004, Melbourne, Australia
[b] Department of Information Technology, Ghent University/iMinds, Gaston Crommenlaan 8 Box 201, Ghent B-9050, Belgium
[c] Department of Epidemiology and Preventive Medicine, School of Public Health and Preventive Medicine, Monash University, The Alfred Centre, 99 Commercial Road, Victoria 3004, Melbourne, Australia
[d] Institute for Risk Assessment Sciences (IRAS), Division Environmental Epidemiology, Utrecht University, Yalelaan 2, 3584 CM Utrecht, The Netherlands
[e] Julius Centre for Health Sciences and Primary Care, University Medical Center, Utrecht, The Netherlands
[f] Imperial College, Department of Epidemiology and Public Health, London, United Kingdom

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ABSTRACT

The aims of this study were to: i) measure personal exposure in the Global System for Mobile communications (GSM) 900 MHz downlink (DL) frequency band with two systems of exposimeters, a personal distributed exposimeter (PDE) and a pair of ExpoM-RFs, ii) compare the GSM 900 MHz DL exposures across various microenvironments in Australia and Belgium, and iii) evaluate the correlation between the PDE and ExpoM-RFs measurements. Personal exposure data were collected using the PDE and two ExpoM-RFs simultaneously across 34 microenvironments (17 each in Australia and Belgium) located in urban, suburban and rural areas. Summary statistics of the electric field strengths (V/m) were computed and compared across similar microenvironments in Australia and Belgium. The personal exposures across urban microenvironments were higher than those in the rural or suburban microenvironments. Likewise, the exposure levels across the outdoor were higher than those for indoor microenvironments. The five highest median exposure levels were: city centre (0.248 V/m), bus (0.124 V/m), railway station (0.105 V/m), mountain/forest (rural) (0.057 V/m), and train (0.055 V/m) [Australia]; and bicycle (urban) (0.238 V/m), tram station (0.238 V/m), city centre (0.156 V/m), residential outdoor (urban) (0.139 V/m) and park (0.124 V/m) [Belgium]. Exposures in the GSM 900 MHz frequency band across most of the microenvironments in Australia were significantly lower than the exposures across the microenvironments in Belgium. Overall correlations between the PDE and the ExpoM-RFs measurements were high. The measured exposure levels were far below the general public reference levels recommended in the guidelines of the ICNIRP and the ARPANSA.

1. Introduction

The exposure of humans to radiofrequency-electromagnetic fields (RF-EMFs) is inevitable, due to the omnipresent RF-EMF sources in the modern environment. There are public concerns for potential health effects caused by the use of RF-EMF associated technologies, mobile phones and base stations (Kim et al., 2014; Tjong et al., 2015; Wiedemann et al., 2014). Furthermore, there is currently a strong need for quantification of personal exposures using objective measures for current and future human epidemiological studies (van Deventer et al., 2011).

The personal exposures from far-field RF-EMF sources, including mobile phone base stations, can be evaluated by performing personal measurements in various microenvironments using exposimeters (Dürrenberger et al., 2014; Joseph et al., 2010; Röösli et al., 2010; Urbinello et al., 2014a). However, exposure evaluations with exposimeters still have limitations (Bhatt et al., 2016), which give rise to measurement uncertainties. The uncertainties can reach up to 25–30 dB (Bolte et al., 2011; Iskra et al., 2011; Neubauer et al., 2010) and include shielding effects of the human body, the multidirectional nature of the incident RF-EMFs, residual calibration, the frequency response of the exposimeter, and the inability to detect signals below the lower detection limits, etc. (Bolte et al., 2011; Gajšek et al., 2015; Iskra et al.,

* Corresponding author.
E-mail addresses: chhavi.bhatt@monash.edu (C.R. Bhatt), Arno.Thielens@intec.ugent.be (A. Thielens), mary.redmayne@monash.edu (M. Redmayne), michael.abramson@monash.edu (M.J. Abramson), Baki.Billah@monash.edu (B. Billah), malcolm.sim@monash.edu (M.R. Sim), R.C.H.Vermeulen@uu.nl (R. Vermeulen), luc.martens@intec.ugent.be (L. Martens), wout.joseph@intec.ugent.be (W. Joseph), geza.benke@monash.edu (G. Benke).

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2011; Mann, 2010; Neubauer et al., 2010). Measurement uncertainties in personal exposimetry could be reduced by employing on-body calibrated exposimeters (Thielens et al., 2015a).

A personal distributed exposimeter (PDE) with multiple RF-EMF antennas, placed on the body, has been developed recently in order to reduce measurement uncertainties related to shielding effects and directionality of the signal (Thielens et al., 2013, 2015a, 2015b; Vanveerdeghem et al., 2015). The PDE systems have been tested to measure far-field exposures from the Global System for Mobile communications (GSM) 900 MHz downlink (DL) and Wi-Fi networks (Thielens et al., 2013, 2015b). In the GSM 900 MHz DL band, the first prototype was developed using three on-body antennas (Thielens et al., 2013), but was not used for actual measurements. A second generation prototype was used for actual exposure measurements (Vanveerdeghem et al., 2015). This system consists of four on-body antennas matched with complementary receiver electronics and is currently the only system available for PDE measurements, which consequently can only consider the GSM 900 MHz DL band at this moment.

Several European studies indicate that mobile phone base stations are a major source of whole body exposure to RF-EMF (Bolte and Eikelboom, 2012; Frei et al., 2009; Gajšek et al., 2015; Joseph et al., 2010; Urbinello et al., 2014b, 2014c; Vermeeren et al., 2013). More specifically, mobile phone base stations are a dominant exposure source to the whole body in urban outdoor environments and on public transport (Joseph et al., 2010; Urbinello et al., 2014a, 2014b).

While much of the information about personal RF-EMF exposure comes from the studies conducted in Europe, similar information from Australia or elsewhere is lacking. There are only limited data on environmental exposure from mobile phone base stations, particularly at locations close to the base stations, that have been reported in Australia (Radio Frequency National Site Archive, 2015; Rowley and Joyner, 2012; Henderson and Bangay, 2006). The utilization of mobile phone technology in Australia has increased substantially during the last two decades. This is similar to what has occurred in Europe, including Belgium, and USA (ACMA paper, 2015; ACMA communications report, 2014). The demands of increased mobile phone signal coverage and signal capacity largely contributed to measured increases in outdoor environmental exposures of 20% to 57% in three European cities (including Gent, Belgium) over the course of one year (Urbinello et al., 2014a). Therefore, a comparative study of personal RF-EMF exposure using similar study protocols, involving countries in Europe and elsewhere was needed.

The purposes of this study were: i) to measure personal exposure in the GSM 900 MHz downlink (DL) frequency band with two systems of exposimeters, the PDE (a novel exposimeter) and a pair of ExpoM-RFs, ii) to compare the exposure levels for selected microenvironments in the two countries, and iii) to assess the correlation between the PDE and ExpoM-RFs measurements.

2. Materials and methods

2.1. Study areas

The study was conducted in urban, suburban, and rural areas in Australia and Belgium (Fig. 1). The measurements were performed by one person (CRB) during 16th April–8th May and 27th March–6th April 2015, respectively. The study regions in Australia included Victoria, and mainly covered the Greater Melbourne region, and a rural site (Cathedral Range State Park). Similarly, Gent and Mol, the provinces of East Flanders and Antwerp respectively, in the Flemish region of Belgium were covered in the study. We considered a region to be urban when the population density was >400 people per square kilometre (Joseph et al., 2010).

A total of 34 matched microenvironments (17 in Australia and 17 in Belgium) were chosen to evaluate personal exposures. A microenvironment is a spatial compartment where a human subject spends time and his/her personal RF-EMF exposure is evaluated for that specific duration (Röösli et al., 2010; Urbinello et al., 2014a, 2014b). The selected microenvironments were similar to those employed in various previous studies (Bolte and Eikelboom, 2012; Frei et al., 2009; Joseph et al., 2010; Röösli et al., 2010; Urbinello et al., 2014a, 2014b). The characteristics of each microenvironment, its spatial characteristics, and the activities undertaken therein by the subject are summarized in Table 1 in Appendix A. The microenvironments were mainly of two types: stationary or mobile. The stationary microenvironments remained fixed while the subject moved around in the microenvironment, whereas the mobile microenvironments moved around during the data collection while the subject generally remained stationary. The mobile microenvironments included bus, train, tram, car and bicycle, whereas stationary microenvironments included the rest, except for subway station/ride, which was a mixed microenvironment.

2.2. On-body calibration procedure

2.2.1. The PDE system

The PDE system was used to perform personal exposure measurements in the GSM 900 downlink (DL) band (925–960 MHz). The PDE system was a collection of three body-worn antennas (see Fig. 2) (2 anterior and 1 posterior) tuned to the mobile phone GSM 900 MHz DL frequency band. The PDE was connected to complementary receiver electronics (Vanveerdeghem et al., 2015) that registered the received

a b

Fig. 1. Maps of a) Australia and b) Belgium showing Melbourne and Gent respectively (Sources: https://commons.wikimedia.org, and http://www.bbc.co.uk/, respectively).

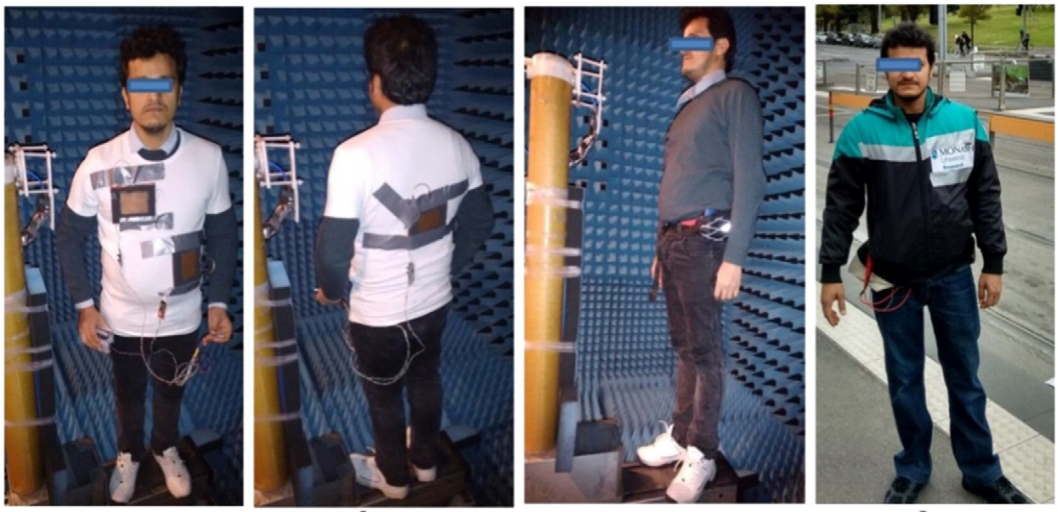

Fig. 2. The human subject performing i) an on-body calibration of the PDE (figures a & b), and ii) ExpoM-RFs (figure c), in Gent, Belgium, ii) exposure measurement at a site in Melbourne, Australia (figure d).

power on the antennas. The E_{inc} (incident electric-field strength) can be determined from the received power on the PDE, using the effective antenna aperture (*AA*) of the set of antennas (Thielens et al., 2015b, 2015c). On-body calibration was performed to determine the *AA*.

2.2.2. The ExpoM-RFs system

The ExpoM-RFs measured electric field strengths (E_{body}) in 16 different frequency bands, including GSM 900 MHz DL. This study only dealt with GSM 900 MHz DL frequency band. ExpoM-RF 64 and ExpoM-RF 40 were used in the calibration process.

2.2.3. The calibration procedure

In this study, we used established on-body calibration procedures (Thielens et al., 2013, 2015a, 2015b, 2015c; Vanveerdeghem et al., 2015). The calibration took place in an anechoic chamber with a transmitting antenna (T_X) on one side of the chamber and a rotational platform on the other side. The T_X emitted a constant output power at 942.5 MHz, thus inducing RF-EMFs that were incident on the rotational platform on which the subject could stand.

The subject (a 35-year-old male subject; height 163 cm and mass 60 kg) participated in the on-body calibration in order to conduct subsequent field measurements. The subject did not carry a mobile phone and did not have any metal objects attached to his body during calibration. The calibration procedure is further described in Appendix B.

2.3. Exposure assessment

The exposure measurement system consisted of the PDE (prototype) system (Gent University/iMinds, Gent, Belgium) and the two above-mentioned ExpoM-RFs (Fields at Work GmbH, Zürich, Switzerland). The PDE antennas were attached to a *T*-shirt; 2 front antennas (1 over the right chest, the other on the left abdominal area), and 1 posterior antenna on the central back (Fig. 2). The antennas were wired to a battery and operated with an on/off switch. Each

Table 2
Personal exposures (E_{rms} in V/m) across various microenvironments in Australia and Belgium [median (25th, 75th percentiles) and range (min, max)].

Microenvironments	Australia		Belgium	
	Median (25th, 75th percentiles)	Range (min, max)	Median (25th, 75th percentiles)	Range (min, max)
Residential outdoor (urban)	0.044 (0.029, 0.075) [2,a]	0.017, 0.197	0.139 (0.094, 0.197) [1,a]	0.022, 0.494
Residential indoor (urban)	0.019 (0.016, 0.024) [2,a]	0.008, 0.047	–	–
Office indoor (urban)	0.018 (0.016, 0.021) [2,a]	0.010, 0.046	0.032 (0.027, 0.039) [2,a]	0.010, 0.091
Park (urban)	0.051 (0.029, 0.065) [2,a]	0.019, 0.156	0.124 (0.091, 0.162) [2,a]	0.034, 0.458
City centre	0.248 (0.102, 0.324) [2,ab]	0.006, 0.647	0.156 (0.115, 0.182) [1,a]	0.057, 0.278
Library (urban)	0.049 (0.036, 0.062) [2,a]	0.014, 0.124	0.110 (0.088, 0.145) [1,a]	0.038, 0.278
Shopping centre (urban)	0.021 (0.019, 0.025) [1,a]	0.015, 0.115	0.028 (0.025, 0.034) [1,a]	0.015, 0.204
Railway station (urban)	0.105 (0.074, 0.117) [2,ab]	0.042, 0.331	0.034 (0.023, 0.169) [1,a]	0.015, 0.534
Tram station (urban)	0.038 (0.030, 0.060) [2,a]	0.007, 0.075	0.238 (0.204, 0.267) [1,a]	0.139, 0.622
Bicycle (urban)	0.017 (0.007, 0.041) [2,ab]	0.007, 0.221	0.238 (0.169, 0.300) [1,a]	0.053, 0.784
Bicycle (rural/suburban)	–	–	0.012 (0.010, 0.013) [1,a]	0.009, 0.035
Bus (urban)	0.124 (0.065, 0.213) [2,a]	0.027, 0.555	0.028 (0.019, 0.049) [2,b]	0.007, 0.556
Car (urban/suburban)	0.006 (0.006, 0.006) [1,a]	0.006, 0.049	0.041 (0.023, 0.065) [2,ab]	0.007, 0.387
Car (rural/suburban)	–	–	0.016 (0.013, 0.020) [1,a]	0.009, 0.070
Tram (urban)	0.041 (0.035, 0.058) [2,a]	0.006, 0.197	0.055 (0.029, 0.124) [1,a]	0.017, 0.441
Train	0.055 (0.030, 0.115) [2,ab]	0.011, 0.534	0.020 (0.017, 0.027) [1,a]	0.011, 0.084
Subway station/ride (urban)	0.031 (0.027, 0.039) [1,a]	0.015, 0.312	–	–
Residential outdoor (rural/suburban)	0.006 (0.006, 0.006) [2,a]	0.006, 0.051	0.014 (0.011, 0.044) [2,a]	0.010, 0.088
Residential indoor (rural/suburban)	–	–	0.017 (0.016, 0.019) [2,a]	0.013, 0.031
Mountain/forest (rural)	0.057 (0.049, 0.061) [1,b]	0.012, 0.068	–	–

1 = single measurement, 2 = repeated measurement; a = 3-antennas' data, b = 2 antennas' data; ab = 3 antennas' data in one measurement and 2 antennas' data in the other measurement.

antenna collected the signals simultaneously. Two ExpoM-RFs were attached to the lateral sides of the hip (one each side) using travellers' money belts.

A light jacket was worn by the subject to cover both exposimeter systems while carrying out the field measurements (Fig. 2). The subject did not have any metal objects attached to his body during the data collection. A diary was maintained in order to record information on activities undertaken during data collection and descriptions of the microenvironments. All measurements were performed during the daytime (9:45 am–6:00 pm) or evening hours (6:00 pm–11:00 pm) on weekdays, except the measurements of residential outdoor and residential indoor (rural/suburban) in Belgium, which were performed during the weekends (2:30–2:45 pm and 11:00–11:15 pm respectively). The RF-EMF measurements during the daytime and evening on weekdays were expected to provide the highest values of exposure (Joseph et al., 2010).

Each measurement duration was 15 min per microenvironment. Urbinello et al. (2014a, 2014b) have employed similar measurement duration to monitor personal exposures. A smart phone was used to monitor measurement time during the measurements; it was in flight mode to prevent it from transmitting and receiving signals during data collection. The measurement interval for the PDE and the ExpoM-RFs were chosen to be 1 and 3 s, respectively.

On average, the PDE collected a total of 900 samples on each antenna per microenvironment measurement session. Similarly, each ExpoM-RF collected 300 data samples per measurement. Most of the microenvironment measurements were performed twice (Table 1 in Appendix A) to check exposure variability.

In Australia, the measurements in three microenvironments involved three and two antennas' data at the time of the first and second measurements, respectively; whereas a microenvironment involved measurement with two antennas (Table 2). Similarly, a microenvironment in Belgium involved two antennas' data during both measurements, and the other microenvironment involved three and two antennas' data during the first and the second measurements respectively (Table 2). The detection range of the PDE (with on-body calibration) was 5.9 mV/m–59 V/m. The detection range for the ExpoM-RFs for GSM 900 MHz DL reported in the datasheet of the devices (without on-body calibration) was 5 mV/m–5 V/m. After an on-body calibration, the detection range of the ExpoM-RFs was estimated at 10 mV/m–10 V/m. Both devices measured the root mean square electric field strengths (E_{rms}) in V/m. The measured data of the PDE were then processed using the corresponding *AA* and detection limit of the relevant pair of antennas. Similarly, geometric mean of the on-body calibration factors of the ExpoM-RFs was used to process the measured ExpoM-RFs data, see Section 3.1.

2.4. Data processing and statistical analysis

The PDE data output provided the incident electric fields for a geometric mean of the given combination of antennas. Geometric means of the electric field signals obtained with two ExpoM-RFs were computed over time within the selected sample intervals using the formula; $Geometric\ mean = (E_{ExpoM\text{-}RF40} \times E_{ExpoM\text{-}RF64})^{1/2}/0.51$, where 0.51 is the correction for the presence of the body (i.e. a division by the average response of the pair of ExpoM-RFs). The normality of the geometric mean data of the PDE and ExpoM-RFs for each microenvironment and each measurement session (i.e. measurement 1 and measurement 2) were examined by Shapiro-Wilk tests of both untransformed and log-transformed data. In addition, visual inspection of histograms and the normal Q-Q plots was also performed. Measurements 1 and 2 represented the first and the second (repeated) measurements, respectively.

Medians (25th and 75th percentiles) and ranges (minimum, maximum) of the electric field strengths were calculated from the geometric means of the PDE and ExpoM-RFs data obtained from the combination of antennas and two ExpoM-RFs, respectively. The values measured by the individual antennas of the PDE and individual ExpoM-RF were not considered in this study. The exposures measured with the ExpoM-RFs were only used while evaluating the agreement between two devices' measurements.

Personal exposure levels were described by summary statistics of the electric field strengths measured with the PDE. The personal exposures across similar microenvironments in Australia ($n = 14$) and Belgium ($n = 14$) were compared. Six microenvironments were excluded from the comparison: residential indoor (urban), subway station/ride (urban), mountain/forest (rural) in Australia ($n = 3$), and bicycle (rural/suburban), residential indoor (rural/suburban) and car (rural/suburban) in Belgium ($n = 3$). These were excluded because each comparable corresponding microenvironment in the other country was not assessed.

The Shapiro-Wilk test and evaluation of histograms and normal Q-Q plots indicated that none of the microenvironments followed a normal or lognormal distribution of the personal exposure electric field levels. Therefore Wilcoxon rank sum tests were performed on the exposure data of the compared microenvironments in order to examine whether the exposures across those microenvironments in Australia and Belgium were different. The assessment of exposure variability during the first and second measurements was done by performing Wilcoxon rank sum tests. Thirteen microenvironments in Australia and 6 microenvironments in Belgium, which had repeated measurements, were evaluated.

The correlations between the PDE and ExpoM-RFs measurements were evaluated on the median exposure data of 34 microenvironments (17 in each country). The evaluation was performed also for 21 stationary (11 in Australia and 10 in Belgium) and 13 mobile microenvironments (6 in Australia and 7 in Belgium).

For all statistical tests, the $p < 0.05$ (two sided) was considered as statistically significant. All data analyses were carried out using MATLAB R2015a (The MathWorks Inc., Natick, Massachusetts, USA) or STATA ver13.1 (StataCorp, College Station, TX, USA).

3. Results

3.1. Calibration of the exposimeter systems

The median antenna aperture of the PDE worn on the body, calculated over 100 repetitions of the same processing, was found to be 1.05 cm^2 (inter quartile range 1.04 cm^2–1.06 cm^2). The value of the prediction interval (PI_{50}) for antenna aperture of the PDE was 3.3 dB.

The median responses of the ExpoM-RFs worn on the body and the geometric average of both ExpoM-RFs, calculated over 100 repetitions of the same processing, were found to be 0.502 (inter quartile range 0.502–0.503) [ExpoM-RF 40], 0.533 (inter quartile range 0.532–0.534) [ExpoM-RF 64], and 0.507 (inter quartile range 0.507–0.508) [geometric average of two ExpoM-RFs].

The values of PI_{50} on the response of the ExpoM-RFs were 5.9 dB (ExpoM-RF 40), 3.6 dB (ExpoM-RF 64) and 4.2 dB for the geometric average of the two ExpoM-RFs.

3.2. Descriptive statistics

The E_{rms} values of all the measured signals were found to be above the lower measurable threshold of the PDE. Table 2 below summarizes the personal exposure levels across different microenvironments in Australia and Belgium.

In Australia, the five highest median exposure levels (from mobile phone base stations) measured were: city centre (0.248 V/m), bus (0.124 V/m), railway station (0.105 V/m), mountain/forest (rural) (0.057 V/m), and train (0.055 V/m). Similarly, the five lowest median exposures measured were: car (urban/suburban) (0.006 V/m),

Table 3
Evaluation of the variability in personal exposure measurements [medians at M_1 (measurement 1) and M_2 (measurement 2) in V/m].

Microenvironments	Countries	Median (25th, 75th percentiles) at M_1	Median (25th, 75th percentiles) at M_2	*P values
Residential outdoor (urban)	Australia [a]	0.055 (0.034, 0.098)	0.041 (0.026, 0.062)	<0.001
Residential indoor (urban)	Australia [a]	0.017 (0.014, 0.031)	0.019 (0.016, 0.023)	0.17
Office indoor (urban)	Australia [a]	0.017 (0.016, 0.019)	0.016 (0.015, 0.023)	0.46
Office indoor (urban)	Belgium [a]	0.033 (0.028, 0.044)	0.034 (0.029, 0.041)	0.29
Park (urban)	Australia [a]	0.046 (0.030, 0.055)	0.055 (0.028, 0.070)	<0.001
Park (urban)	Belgium [a]	0.106 (0.078, 0.156)	0.106 (0.084, 0.134)	0.91
City centre	Australia [ab]	0.324 (0.289, 0.386)	0.081 (0.015, 0.162)	<0.001
Library (urban)	Australia [a]	0.055 (0.047, 0.062)	0.055 (0.049, 0.065)	0.17
Railway station (urban)	Australia [ab]	0.117 (0.105, 0.132)	0.081 (0.057, 0.106)	<0.001
Tram station (urban)	Australia [a]	0.031 (0.028, 0.035)	0.060 (0.053, 0.062)	<0.001
Bicycle (urban)	Australia [ab]	0.035 (0.020, 0.057)	0.007 (0.007, 0.007)	<0.001
Bus (urban)	Australia [a]	0.115 (0.053, 0.204)	0.134 (0.069, 0.238)	<0.001
Bus (urban)	Belgium [b]	0.046 (0.024, 0.069)	0.021 (0.018, 0.030)	<0.001
Car (urban)	Belgium [ab]	0.057 (0.044, 0.088)	0.022 (0.014, 0.038)	<0.001
Tram (urban)	Australia [a]	0.041 (0.036, 0.049)	0.036 (0.029, 0.053)	<0.001
Train	Australia [ab]	0.058 (0.024, 0.137)	0.057 (0.033, 0.102)	0.024
Residential indoor (rural/suburban)	Belgium [a]	0.019 (0.017, 0.021)	0.015 (0.015, 0.016)	<0.001
Residential outdoor (rural/suburban)	Australia [a]	0.006 (0.005, 0.006)	0.006 (0.005, 0.006)	0.22
Residential outdoor (rural/suburban)	Belgium [a]	0.047 (0.037, 0.057)	0.011 (0.011, 0.012)	<0.001

a = 3-antennas' data, b = 2 antennas' data; b = 2 antennas' data; ab = 3 antennas' data in one measurement and 2 antennas' data in the other measurement,
* P values <0.05 statistically significant different exposure levels.

residential outdoor (rural/suburban) (0.006 V/m), bicycle (urban) (0.017 V/m), office indoor (urban) (0.018 V/m), and residential indoor (urban) (0.019 V/m).

In Belgium, the five highest median exposures measured were: bicycle (urban) (0.238 V/m), tram station (0.238 V/m), city centre (0.156 V/m), residential outdoor (urban) (0.139 V/m), and park (0.124 V/m). Similarly, the five lowest exposure levels measured were: bicycle (rural/suburban) (0.012 V/m), residential outdoor (rural/suburban) (0.014 V/m), car (rural/suburban) (0.016 V/m), residential indoor (rural/suburban) (0.017 V/m), and train (0.020 V/m).

3.3. Comparison of exposure levels in Australia and Belgium

We found that personal exposures across most of the microenvironments in Australia were significantly lower ($p < 0.05$) than the exposure across the microenvironments in Belgium. However, there were a few microenvironments where the exposure in Australia was higher ($p < 0.05$) than the corresponding exposure in Belgium. For instance, the city centre results in Melbourne were significantly higher ($p < 0.001$) than the exposure level at the city centre of Gent, as were exposures in the Melbourne train and during a bus ride, than those in Gent.

3.4. Evaluation of the variability of exposures

Table 3 shows the results of the Wilcoxon rank sum tests that was were performed to evaluate if the repeated measurements provided similar exposure levels. The analysis showed that the majority of the microenvironments (13 of 19) provided significantly different median exposure levels at the measurements 1 and 2, suggesting that both measurements had highly varied exposures. The microenvironments demonstrating similar exposures at both measurements were: residential indoor (urban), office indoor (urban), library (urban), and residential outdoor (rural/suburban) [Australia], and office indoor (urban) and park (urban) [Belgium].

Spatial matching of the repeated stationary microenvironmental measurements was ensured by walking across the same area and towards the same direction. In case of the repeated mobile microenvironments, the spatial matching was accomplished by sitting/standing at the same spot/around the same positions with respect to window and carriage dimension. All mobile microenvironment measurements, except for car (urban) and bus (urban) in Belgium, were performed on exactly the same routes. The temporal matching, for most of the measurements, was ensured by performing the measurements (1st and 2nd) at similar times of the day, such as morning, evening or night.

3.5. Correlation between the PDE and the ExpoM-RFs measurements

The overall Spearman correlation coefficient for all microenvironments was 0.63 ($p < 0.001$). Similarly, the correlation coefficients for stationary and mobile microenvironments were 0.71 ($p < 0.001$) and 0.28 ($p = 0.24$), respectively.

4. Discussion

We have reported the personal far-field RF-EMF exposures from the GSM 900 MHz down-link frequency band across the various microenvironments in Australia and Belgium, using a novel on-body calibrated PDE system. Monitoring of exposures across various microenvironments, including those investigated in our work, is one of the approaches to assess human exposure (Dürrenberger et al., 2014; Joseph et al., 2010; Röösli et al., 2010; Urbinello et al., 2014a).

4.1. Exposure characteristics in Australia and Belgium

The personal exposure levels experienced across various microenvironments varied according to the location and type of microenvironment. Previous studies also found variation in exposure across various microenvironments (Bolte and Eikelboom, 2012; Frei et al., 2009; Joseph et al., 2010; Urbinello et al., 2014a). Spatial factors, such as the location of the measurement sites (urban, suburban, rural, outdoor, indoor etc.), distance to nearby base stations; temporal factors (e.g. day, time and season when the measurements were performed), and existing mobile phone traffic are likely to impact the levels of far-field personal exposures (Bolte and Eikelboom, 2012; Joseph and Verloock, 2010; Manassas et al., 2012; Urbinello et al., 2014b; Vermeeren et al., 2013).

The exposure levels found in our study were well below the reference levels for the general public as provided in the guidelines of the International Commission on Non-Ionizing Radiation Protection (ICNIRP, 1998) and the Australian Radiation Protection and Nuclear Safety Agency (Radiation Protection Standard, 2002). The mean exposures in Australia measured were in the range of 0.02–3.65% of the reference level, whereas those in Belgium were in the range of 0.03–2.73% of the reference level. The reference level for GSM 900 MHz DL specified by the guidelines is equivalent to 42 V/m [$Erms = 1.37 \times (f)0.5$ V/m] at

942.5 MHz. However, it should be borne in mind that these guidelines are designed to protect against immediate RF-EMF effects from elevated tissue temperatures from absorbed energy during exposure and do not cover possible health or bio-effects related to long-term low-level exposures.

The city centre of Melbourne, which exhibited the highest exposure, is a central business district with strong cell phone network coverage (OpenSignal, 2015; Radio Frequency National Site Archive, 2015). Furthermore, other high exposure microenvironments in Australia were either characterised with densely sited mobile phone towers [e.g. railway station, residential outdoor (urban)] or use of public transport (e.g. bus and train). Except for bicycle (urban), the lowest exposure contributing microenvironments in Australia were either located in rural and suburban regions of Melbourne [car (urban/suburban), residential outdoor (rural/suburban)], or were indoor microenvironments [office indoor and residential indoor (urban)]. The rural and suburban microenvironments in Melbourne were located about 20 km northeast of Melbourne's city centre with relatively fewer mobile phone towers (OpenSignal, 2015; Radio Frequency National Site Archive, 2015) and lower population density.

Of all microenvironments in Belgium, the tram station and bicycle provided the highest exposures, mainly due to denser base stations. During the measurements, two mobile phone towers were sited near the tram station and three mobile phone towers were situated in the subject's line-of-sight while performing the bicycle measurements. The other high exposure microenvironments, city centre, residential outdoor and park were characterised by higher mobile phone tower density and stronger network signal strength (Antenna Site Register, 2015; OpenSignal, 2015). As visualised on online databases of mobile phone base stations and signal strength, the density of base stations and signal strengths across these areas is relatively high compared to that in rural and suburban regions of Belgium (Mol). The microenvironments located in the rural and suburban regions of Mol (e.g. bicycle, residential outdoor, residential indoor, and car] provided the lowest exposure. These regions only have a few base stations, low signal strength and low population density.

In general, the exposures measured across most microenvironments in Australia were much lower than those measured across similar microenvironments in Belgium. Higher population density and building characteristics (densely sited and fewer tall buildings) may have attributed to the higher observed exposures across most of the microenvironments in Belgium (Gent) compared to those observed across the microenvironments in Australia (Melbourne). Interestingly, the city centre and train in Australia characterised higher exposures compared to those of the city centre of Gent and the train in Belgium. This is due to the fact that Melbourne city centre has many densely sited base stations and high rise buildings compared to Gent. In the case of the train in Melbourne, a train travelled within the urban regions with many people travelling on board. Whereas the train from Gent to Antwerp mostly travelled through suburban and rural regions, where the mobile phone network was expected to be weaker. Furthermore, trains in Belgium have windows with metallic coatings on them, which make them very good Faraday cages, subsequently providing low downlink exposure levels. These reasons probably explained why the train in Melbourne provided higher downlink exposure than in Gent. A rural site, mountain/forest, provided high exposure level, which could be due to its location with respect to the nearby base station, and we also observed a person making mobile phone calls when the measurements at the site were performed. The measurements in Belgium and Australia were performed during Spring and Autumn respectively. Furthermore, RF-EMF is also absorbed by the leaves of trees, which would vary according to the amount of foliage present according to different seasons of the year. Mobile phone base stations vary their broadcasting power to provide optimum signal coverage (Bolte and Eikelboom, 2012). Finally, the two countries also have some differences in terms of their natural environments and physical infrastructures, which may influence the mobile phone network in specific areas. The mobile telecommunication systems have been evolving from 2G to 3G worldwide, including in Australia and Belgium (International Telecommunication Union, 2010). The difference in mobile phone base station exposure between these two countries is therefore unlikely to be stable in time.

It was also observed that the personal exposures in urban microenvironments were much higher than those in rural and suburban microenvironments in both Australia and Belgium. Furthermore, the exposure levels across indoor microenvironments were much lower than those across the outdoor microenvironments. It is well known that microenvironments in an urban area generally provide higher GSM DL exposure compared to those located in rural or suburban areas (Bolte and Eikelboom, 2012; Joseph et al., 2010; Urbinello et al., 2014a; Vermeeren et al., 2013). Likewise, indoor microenvironments provide lower GSM DL exposure than outdoor microenvironments (Bolte and Eikelboom, 2012; Joseph et al., 2010; Urbinello et al., 2014a).

The exposure levels found in our study can be compared to those reported by previous studies conducted in Belgium and other parts of Europe (e. g. Joseph et al., 2010; Urbinello et al., 2014a, 2014b). Joseph et al. (2010) examined the combined downlink (GSM 900, GSM 1800 and UMTS 2100) personal exposure across similar microenvironments in Belgium, Switzerland, Slovenia, Hungary, and the Netherlands, and reported mean exposures for similar microenvironments such as urban outdoor, office, train, car/bus, urban residential (indoor). Similarly, Urbinello et al. (2014a, 2014b) also evaluated the combined downlink personal exposure across similar microenvironments in Gent and Brussels (Belgium) and Basel (Switzerland) – residential outdoor (central urban), residential outdoor, city centre, suburban outdoor, train, tram/metro, bus, train station and shopping centre. In general, the mean exposures reported in these studies were slightly lower than those reported in our study (mean exposure values not shown in Table 2). We need to be cautious comparing the exposure reported in our study with those reported in previous studies. The main reasons are: i) we employed an on-body calibrated exposimeter with 3 antennas while those studies used a free space calibrated, single antenna exposimeter (EME Spy) with different measurement intervals, ii) we have only measured GSM 900 MHz DL whereas these studies measured combined downlink signals of three frequency bands. Furthermore, the spatial and temporal characteristics of measurements and measured microenvironments applicable to these studies may have also differed.

Our study demonstrated that GSM 900 MHz DL signals may be highly variable in the same microenvironment on different days. Urbinello et al. (2014c) showed that the environmental exposure levels of mobile phone DL signals across the same areas demonstrated variability in exposure levels. In general, diurnal variation in mobile phone signals in human environments is possible according to spatio-temporal factors (Manassas et al., 2012; Vermeeren et al., 2013; Urbinello et al., 2014c). The true mean exposure values in the microenvironments are unknown, it is simply proposed that two measurements should get a closer estimate than one. Since the path/occupancy during the measurements were nearly identical for most of the microenvironments, it is therefore unlikely that exposure variation can be attributed only to the small potential differences in paths or occupancies in the successive measurements.

The Spearman correlations between the exposure measured with the PDE and that measured with the ExpoM-RFs for all microenvironments were high. The correlation between the exposure measured with the PDE and that measured with the ExpoM-RFs seemed to be higher in the case of the Belgian microenvironments compared to the Australian microenvironments (results not shown). This is likely because overall exposure levels in Australia were lower than in Belgium. The correlation was much stronger in stationary microenvironments compared than mobile microenvironments (transportation). This may be due to the fact that the subject was essentially stationary (seated or standing only) in the mobile microenvironments. On the other hand, the subject moved across the stationary microenvironments, allowing some averaging out of body shielding.

4.2. Calibration of the exposimeters

A median antenna aperture of the PDE worn on the body was 1.05 cm^2. This is lower than the values found in Vanveerdeghem et al. (2015) (6.6 cm^2) and Thielens et al. (2015c) (6.1 cm^2). We attribute this to the different on-body setup (3 antennas instead of four) and the different assumption on the incident polarizations. In this paper, no assumptions were made on the incident polarization, since the PDE was to be used in different microenvironments that all have their own characteristic polarization distribution. Whereas Vanveerdeghem et al. (2015) (6.6 cm^2) and Thielens et al. (2015c) used the PDE only in an urban environment and consequently a-priori assumptions could be made on incident polarizations. However, the antenna aperture is in the same order of magnitude and realistic for this type of on-body antenna (Thielens et al., 2015c; Vanveerdeghem et al., 2015). The corresponding value of the PI_{50} for antenna aperture of the PDE was 3.3 dB, which is much lower than measured in our study for the individual antennas (i.e.13.6 dB, 6.5 dB, and 6.1 dB). The value was also lower than that reported for single antennas in the same frequency band (Thielens et al., 2013, 2015c; Vanveerdeghem et al., 2015). This indicates that averaging over multiple antennas on the body reduces the variation on the antenna aperture. In Thielens et al. (2013), PI_{50} value of 4.5 dB was measured for a different set-up with three antennas on the body, which indicates that the on-body setup used in this study is closer to an isotropic antenna. An isotropic antenna allows measurements with the same intensity of signals to be performed irrespective of the measurement direction. In Thielens et al. (2015c) a setup with four antennas on the body yielded a slightly lower PI_{50} of 3.1 dB, which was to be expected since more antennas on the body leads to lower PI_{50} values.

The responses of the ExpoM-RFs indicated that the devices underestimated the incident electric field strengths by a factor of approximately 2. The PI_{50} of the geometric average of the two ExpoM-RFs was found to be lower than that of one of the individual ExpoM-RFs (i.e. ExpoM-RF 40). The responses and PI_{50} values of the ExpoM-RFs can be compared to those observed in previous studies. Bolte et al. (2011) measured responses in the GSM 900 MHz DL band between −20 dB and +3 dB were on the body, with median responses below 0 dB (a factor of 1), which agrees with our results. Thielens et al. (2015a) reported values between −10 dB and +5 dB in the same frequency band, with a median underestimation, which is in line with our calibration results. The PI_{50} value observed in our study was lower than what was found for a single exposimeter in other studies in the same frequency band of GSM 900 MHz DL. In Bolte et al. (2011), a single exposimeter (EME Spy 121) was worn on the right hip of a subject rotated over 360° under exposure in the same frequency band. PI_{50} values of 6.5 dB and 15.5 dB were measured for two orthogonal polarizations. Thielens et al. (2015a), measured PI_{50} values of 8.3 dB and 9.6 dB for an exposimeter (EME Spy 140) placed on the right and left hips, respectively. In the same study, a value of 4.6 dB was found for an average over the two exposimeters worn on both hips, which corresponds very well with the 4.2 dB observed in our study.

4.3. Strengths, limitations and implications

To our knowledge, this is the first microenvironmental exposure study to evaluate RF-EMF exposures with the use of a novel, on-body calibrated system of exposimeter, with multiple antennas. The study also provides a basis for a direct valid comparison of exposures across the microenvironments in Australia and Belgium with different geophysical, environment and weather conditions. Furthermore, this study evaluates the correlation between the PDE and the ExpoM-RFs measurements while measuring GSM 900 MHz DL personal exposure.

All the received RF-EMF signals collected in this study were above the lower measurable threshold of the PDE. This is a major strength of this study as it meant there was no issue related to measurements below the lower detection threshold, which has been noted as a major challenge in exposure assessment (Bolte and Eikelboom, 2012; Frei et al., 2009; Joseph et al., 2010; Juhász et al., 2011; Urbinello et al., 2014b). Our study employed ExpoM-RFs, which demonstrated no problem with the issue of detection threshold. Another major strength of our study is that this approach minimised the measurement uncertainties related to body shielding as the PDE consisted of three antennas, which would be expected to provide a much more accurate representation of true personal exposure with fewer measurement uncertainties.

The limitations associated with the study were: i) only GSM 900 MHz DL frequency was considered, ii) the personal exposure was measured only for few selected microenvironments, which means the exposures could not be generalised to other microenvironments, ii) not all measurements were repeated and data were not always obtained with all three antennas of the PDE, iii) each measurement duration was only 15 min.

The feasibility of the PDE system for assessing RF-EMF exposures in future epidemiological studies was demonstrated. Therefore, this study contributes towards an improved exposure assessment approach for RF-EMF epidemiological studies. However the use of an on-body calibrated exposimeter in epidemiological research may not be the most pragmatic approach, since an on-body calibration of the human subject is time intensive and costly work, which is not practicable for large number of subjects in epidemiological studies. In addition, we do not yet know how a limited number of on-body calibrations on a set of subjects can be translated into a general calibration factor valid for the whole population (potentially taking into account body types). Currently, the PDE is being expanded to other downlink frequency bands using multi-band antennas combined with RF nodes tuned to different frequency bands, in order to be able to measure exposure in different RF frequency bands simultaneously using the same approach.

5. Conclusions

An on-body calibrated PDE was employed, for the first time, to evaluate micro-environmental personal exposure to mobile phone base stations GSM 900 MHz downlink in Australia and Belgium. The study revealed that the personal exposure levels measured in Australian microenvironments were generally lower than those in the Belgian microenvironments. The personal exposures across urban microenvironments were higher than those in the rural and suburban microenvironments. Likewise, the exposure levels across the outdoor microenvironments were much higher than those across the indoor microenvironments. A majority of the second measurements in the same site provided highly varied exposures. Overall, the PDE and the ExpoM-RFs measurements demonstrated good correlation. The study confirmed that the personal exposure levels reported in our study were well below the general public reference levels.

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Appendix A

Table 1
A summary of the microenvironments, their characteristics and the associated activities of the subject.

Microenvironments	Countries	Study sites and characteristics	Activities
Residential outdoor (urban)	Australia[2]	Windsor, Melbourne; attached houses mostly up to 2 storeys, few >3–6 storey buildings	Walking through streets
	Belgium[1]	Gent-Ledeberg; attached houses mostly up to 3 storeys, busy streets, and a church	
Residential indoor (urban)	Australia[2]	Prahran townhouse, ground floor	Walking inside the different rooms of the house
Office indoor (urban)	Australia[2]	Commercial Rd, Melbourne (5th floor); a 7-storey university building, multistorey hospital buildings and academic centres, a park and residential area nearby	Sitting on the chair at the working desk, walking around the office rooms
	Belgium[2]	Gaston Crommenlaan, Gent (2nd and 3rd floor); a typical multistorey public office building	
Park (urban)	Australia[2]	Fawkner Park, South Yarra, Melbourne; a typical public park with many trees, roads surrounding the park with closely attached buildings/houses on the two sides of park, bus/tram stations nearby	Walking around the park
	Belgium[2]	Koning Albertpark, Ghent; a typical public park, roads surrounding the park with closely attached buildings/houses on the two sides of park, bus/tram stations nearby	
City centre	Australia[2]	Federation Square, Melbourne; an open city area with bus/tram station, central business district with many tall buildings, including few up to >50 storeys, Yarra river nearby	Walking around the city square
	Belgium[1]	Korenmarkt, Gent; an open city area with bus/tram station, church and other historical buildings nearby	
Library (urban)	Australia[2]	Prahran, Melbourne; a public library with 25–30 people inside, densely packed area with attached buildings/houses mostly up to 3–4 storeys	Walking inside the library, checking books, reading newspapers (standing)
	Belgium[1]	Zuid, Ghent; a public library with two levels, bus and tram station nearby, a park on its one side and city buildings around	
Shopping centre (urban)	Australia[1]	Bourke Street, Melbourne; a 2-storey shopping mall	Walking inside the mall as a customer
	Belgium[1]	Zuid, Gent; 5-storey shopping mall with an open space in the centre of the building	
Railway station (urban)	Australia[2]	Southern Cross Station, Melbourne; the largest train station in Victoria with regional railway and city metro networks (2-storey), retail stores and cafes	Standing and walking in the waiting hall of the station
	Belgium[1]	Gent-Sint-Pieters railway station; the main railway station in Gent and one of the busiest railway stations in Belgium, retail stores and cafes	
Tram station (urban)	Australia[2]	Domain Interchange, Melbourne; a typical tram station with 15–20 people around, business and public buildings nearby	Standing and walking around the tram waiting points
	Belgium[1]	Zuid station, Gent; a typical tram/bus station with 20–30 people around, buildings and shopping centres nearby	
Bicycle (urban)	Australia[2]	Commercial road–Birdwood Ave, Melbourne; park and attached houses/multistorey buildings (up to 10 levels) on the both sides of the road, trees along the roadside	Riding a bicycle around
	Belgium[1]	Gaston Crommenlaan and Zuid, Gent; roads (with a flyover), park and attached houses and multistorey buildings on the sides of the roads and park	Riding a bicycle around
Bus (urban)	Australia[2]	Alfred hospital–Cardigan street, Melbourne; the public bus plied through the area with mostly 3–4 storey houses and a few big buildings, on average 10–15 people on board	Standing and sitting on a seat located in the middle part of the bus
	Belgium[2]	Zuid–Merelbeke, and Zuid–Fratersplein, Gent; the public bus plied through the area with mostly 3–4 storey houses and few big buildings, on average 20–25 people on board	
Car (urban)	Australia[1]	Eaglemont–Eltham, Melbourne; streets with normal urban/suburban traffic and densely packed area and detached houses mostly up to 2–3 storey	Sitting on the front seat of the car
	Belgium[2]	Gaston Crommenlaan – Dampoort, and Gaston Crommenlaan- Sint-Pieters station; streets with busy traffic and densely packed areas with some tall public and commercial buildings	
Tram (urban)	Australia[2]	The Alfred hospital–Collins street, Melbourne; on average 20–25 people on board	Standing and sitting on a seat
	Belgium[1]	Jacques Eggermontstraat–Zwijnaarde, Gent; on average 15–20 people on board	
Train	Australia[2]	Flinders Street–Elsternwick, Melbourne (urban), on average 20–30 people on board	Standing, sitting on a seat
	Belgium[1]	Gent–Antwerp (urban and suburban), on average 20–30 people on board	Standing, sitting on a seat
Bicycle (rural/suburban)	Belgium[1]	Boeretang, Mol; a few scattered houses up to 3 storey, a pine tree forest and open agricultural fields, ~3 km from a small town (Mol)	Riding a bicycle around
Car (rural/suburban)	Belgium[1]	Boeretang–Mol; car ride via areas with agricultural fields, forests, and residential sites	Sitting on the front seat of the car
Residential indoor (rural/suburban)	Belgium[2]	Boeretang, Mol; a 3-storey residential quarter, a pine tree forest, agricultural fields and a canal around	Walking and sitting in the common room, kitchen, etc.
Residential outdoor (rural/suburban)	Australia[2]	Tarrawarra, Victoria; few scattered houses, agricultural fields	Walking around the area
	Belgium[2]	Boeretang, Mol; a few scattered houses, pine tree forests, a canal and agricultural fields around	
Subway station/ride (urban)	Australia[1]	Parliament–Flagstaff, Melbourne; a typical subway station with 20–30 people around and 20–25 people on the train carriage	Standing both at the station and on the metro
Mountain/forest (rural)	Australia[1]	Cathedral Range State Park, Taggerty, Victoria; forested hills, one person around	Walking along trails in forest area

1 = single measurement, 2 = repeated (second) measurement.

Appendix B

On-body calibration procedure

In step one, the E_{inc} was measured without the subject present in the fully-anechoic chamber. The measurements of E_{inc} were carried out along the axis of rotation of the platform using a NBM-550 broadband field meter (Narda, Hauppauge, NY, USA). The E_{inc} values were then averaged over the height of the subject (ICNIRP, 1998). This procedure was repeated for two orthogonal polarizations of the T_X: parallel to the axis of rotation (V-polarization) and parallel to the floor of the chamber (H-polarization).

In step two, the subject equipped with the PDE stood on the rotational platform in the far field of the T_X. Three on-body antennas (Thielens et al., 2013; Vanveerdeghem et al., 2015) were placed on the locations shown in Fig. 1a & b. The antennas used in this study were linearly polarized planar inverted F-antennas (Thielens et al., 2013; Vanveerdeghem et al., 2015). The two antennas placed on the front of the torso had orthogonal polarizations, which enabled the device to measure two orthogonal incident far-field polarizations. The antennas were connected, using a shielded SubMiniature version A cable, with RF nodes that contained a surface acoustic wave filter tuned to the 900 MHz downlink band (925–960 MHz). The SAW filter provided an out-of-band isolation of more than 23 dB (Vanveerdeghem et al., 2015). The cables shown in Fig. 1 were used to connect the RF nodes with a battery which was worn on the hips of the subject and did not influence the RF performance of the PDE. The cables and the battery were included in the on-body calibration. The subject was rotated over 360° in azimuthal direction from a constant electric field (E_{inc}), which was V-polarized during the first rotation and then H-polarized. This rotation represented the unknown orientation of the subject in an exposure situation (Thielens et al., 2013). During the rotation the antennas recorded received powers (P_r) on the body. These received powers depend on the rotational angle, due to shadowing of the body (Thielens et al., 2013, 2015b; Vanveerdeghem et al., 2015), and the polarization of the T_X.

The received powers (P_r) were related to the incident electric field strength (E_{inc}) through the effective antenna aperture (AA):

$$AA = \frac{377 \times P_r}{{E_{inc}}^2}$$

Since P_r depends on the angle of incidence, the AA will have a distribution. In determining its distribution, we assumed both polarizations to be equally likely to occur. The distribution of AA was characterised by its median value [p_{50} (AA)] and 50% prediction interval PI_{50} (with p_{25} (AA) and p_{75} (AA), the 25th and 75th percentile of the distribution of AA):

$$PI_{50} = \frac{p_{75}(AA)}{p_{25}(AA)}$$

A perfect exposimeter, i.e. an antenna with a constant AA, will have a $PI_{50} = 1$, so a value close to one is desirable.

During measurements, the incident field strengths can be estimated from the measured received powers (P_r) using this antenna aperture. In this study, we estimated the incident field strength (E_{inc}), using the median AA [p_{50} (AA)]:

$$E_{inc} = \sqrt{\frac{377 \times P_r}{p_{50}(AA)}}$$

In step three, two ExpoM-RFs were employed in the on-body calibration process to determine the relationship between the incident electric field strengths (E_{inc}) and the electric field strengths on the body (E_{body}). These devices are meant to measure E_{inc}, but since they were worn on the body during measurements, they registered E_{body} instead (Bolte et al., 2011; Thielens et al., 2015a). The human subject equipped with the ExpoM-RFs (as shown in Fig. 1c) stood on the rotational platform in the far field of the T_X. Two ExpoM-RFs were placed to the body (Thielens et al., 2013; Vanveerdeghem et al., 2015) on the locations of each hip. The subject was rotated over 360° in azimuthal direction, while being exposed to a constant electric field (E_{inc}), which is first V-polarized and then H-polarized. This rotation represented the unknown orientation of the subject in an exposure situation (Thielens et al., 2013). During the rotation, the ExpoM-RFs recorded the electric fields on the body (E_{body}). These on-body fields and received powers depend on the rotational angle, due to shadowing of the body (Thielens et al., 2013, 2015b; Vanveerdeghem et al., 2015), and the polarization of the T_X. The E_{body} values were not the same as the incident values (E_{inc}) (Thielens et al., 2015a), therefore, the response (R) of the ExpoM-RFs was evaluated as:

$$R = \frac{E_{body}}{E_{inc}}$$

$R > 1$ and < 1 indicated an overestimation or an underestimation respectively. R is not a constant and will have a certain distribution (Thielens et al., 2015a) for each of the two measured orientations of the T_X. In the processing of the results, we made no a-priori assumptions on the incident polarization of the realistic fields and thus assumed each polarization to be equally likely. Therefore, all measured R values were combined in one distribution characterised by its median value (p50(R)) and 50% prediction interval (PI_{50}):

$$PI_{50} = \frac{p_{75}(R)}{p_{25}(R)}$$

with $p75(R)$ and $p25(R)$ indicating the 75th and 25th percentiles of R, respectively. During measurements, the incident field strengths can be estimated from the measured electric field strengths (E_{meas}) using this response. We estimated the incident field strength ($\mathrm{E_{inc}}$), using the median ($p50(R)$):

$$\mathrm{E_{inc}} = \frac{\mathrm{E_{meas}}}{\mathrm{p_{50}(R)}}$$

with E_{meas} the geometric averaged measured electric field strength.

The used calibration procedure is valid for far-field exposure, but might not be suitable for sources close to the body, such as mobile phones or personal devices, which might cause a large variation of the electric field strength on the body. The calibration procedure can be used in this study, where far-field, downlink exposure around 900 MHz is studied.

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