# Assessment of personal exposure from radiofrequency-electromagnetic fields in Australia and Belgium using on-body calibrated exposimeters

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## ABSTRACT

The purposes of this study were: i) to demonstrate the assessment of personal exposure from various RF-EMF sources across different microenvironments in Australia and Belgium, with two *on-body* calibrated exposimeters, in contrast to earlier studies which employed single, non-on-body calibrated exposimeters; ii) to systematically evaluate the performance of the exposimeters using (on-body) calibration and cross-talk measurements; and iii) to compare the exposure levels measured for one site in each of several selected microenvironments in the two countries. A human subject took part in an on-body calibration of the exposimeter in an anechoic chamber. The same subject collected data on personal exposures across 38 microenvironments (19 in each country) situated in urban, suburban and rural regions. Median personal RF-EMF exposures were estimated: i) of all microenvironments, and ii) across each microenvironment, in two countries. The exposures were then compared across similar microenvironments in two countries (17 in each country).

The three highest median total exposure levels were: city center (4.33 V/m), residential outdoor (urban) (0.75 V/m), and a park (0.75 V/m) [Australia]; and a tram station (1.95 V/m), city center (0.95 V/m), and a park (0.90 V/m) [Belgium]. The exposures across nine microenvironments in Melbourne, Australia were lower than the exposures across corresponding microenvironments in Ghent, Belgium ($p < 0.05$). The personal exposures across urban microenvironments were higher than those for rural or suburban microenvironments. Similarly, the exposure levels across outdoor microenvironments were higher than those for indoor microenvironments.

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## 1. Introduction

Concern regarding potential health and biological effects in humans from made sources of radiofrequency-electromagnetic fields (RF-EMFs) exposure has increased in the last decade. The International Agency for Research on Cancer has listed RF-EMF as a possible human carcinogen (Group 2B) (Baan et al., 2011). Furthermore, the World Health Organization emphasized the need of evaluation of personal exposures, from multiple RF-EMF sources for human epidemiological studies using objective measurements (van Deventer et al., 2011).

Personal RF-EMF exposures from far-field RF-EMF sources, such as those from mobile phone base stations, TV/radio signals, Wireless-Fidelity (Wi-Fi), have been evaluated employing exposimeters (Dürrenberger et al., 2014; Joseph et al., 2010; Röösli et al., 2010; Sagar et al., 2016; Urbinello et al., 2014a). These studies used a single exposimeter worn by human subjects to

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measure whole body RF-EMF exposure, but the exposimeters were not calibrated on body. In fact the use of a single exposimeter, may result in measurement uncertainties, particularly those related to the body shielding effects, residual calibration, and the frequency response of the measurement device (Bolte et al., 2011; Gajšek et al., 2015; Iskra et al., 2010, 2011b; Mann, 2010; Neubauer et al., 2010). Iskra et al. (2010, 2011) suggested that the use of two exposimeters placed on different locations on the body may minimize the measurement uncertainties. It has also been demonstrated that wearing two *on-body* calibrated exposimeters, one on each hip, provided more accurate personal exposure measurements with a lower measurement uncertainty (Thielens et al., 2015a).

Studies investigating personal exposure levels from various far-field RF-EMF sources have been mainly conducted in European countries (Bolte and Eikelboom, 2012; Frei et al., 2009; Gajšek et al., 2015; Joseph et al., 2010; Sagar et al., 2016; Urbinello et al., 2014b, 2014c; Vermeeren et al., 2013). There is a paucity of similar comparable data from elsewhere, including Australia. Therefore, a comparative study employing similar study protocols, involving countries outside Europe would be informative to the rest of the world. Only limited information has been reported on environmental exposure levels from mobile phone base stations and other RF-EMF sources in Australia (Henderson et al., 2014; Henderson and Bangay, 2006; Rowley and Joyner, 2012). Furthermore, we have recently published personal exposure data from 900 MHz mobile phone base station downlink in Australia and Belgium (Bhatt et al., 2016a).

The aims of this study were: i) to demonstrate the assessment of personal exposure from various RF-EMF sources across different microenvironments in Australia and Belgium, with two *on-body* calibrated exposimeters, in contrast to earlier studies which employed single, non-on-body calibrated exposimeters; ii) to systematically evaluate the performance of the exposimeters using (on-body) calibration and cross-talk measurements; and iii) to compare the exposure levels measured for one site in each of several selected microenvironments in the two countries.

## 2. Materials and methods

### 2.1. Study areas

The study was carried out in urban, suburban, and rural sites in Australia and Belgium. The microenviromental personal measurements were performed on a single person (CRB) during 7th April–8th May and 27th March–6th April 2015, respectively. The study areas in Australia mainly covered the urban and suburban regions of Greater Melbourne, and a rural site (Cathedral Range State Park). Similarly, urban and suburban regions of Ghent and rural regions of Mol in the Flemish region of Belgium were included in the study. A region was considered to be urban when the population density was > 400 people per square kilometre (Joseph et al., 2010).

A total of 38 microenvironments (Table A1, Appendix A), 19 each in Australia and in Belgium, were selected to evaluate personal exposures. Of them, the 34 matched microenvironments (17 each in each country) were: residential outdoor (urban), residential indoor (urban), office indoor (urban), park (urban), city center, library (urban), shopping center (urban), train station (urban), tram station (urban), bicycle (urban), bus (urban), car (rural/suburban), tram (urban), train, residential outdoor (rural/suburban), residential indoor (rural/suburban), and airport. In addition, subway station/ride (urban), mountain/forest (rural) in Australia, and bicycle (rural/suburban) and car (urban/suburban) in Belgium were also measured. These microenvironments have been

described more fully in our previous paper (Bhatt et al., 2016a), and were similar to those of other studies (Bolte and Eikelboom, 2012; Frei et al., 2009; Joseph et al., 2010; Röösli et al., 2010; Urbinello et al., 2014a, 2014b). We also evaluated the indoor exposures in airports of both countries, Tullamarine International Airport, Melbourne, and Brussels International Airport, Brussels.

The microenvironments were primarily 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, whilst the subject essentially remained stationary. The mobile microenvironments included bus, train, tram, car and bicycle, whereas stationary microenvironments included the rest, except for subway station and ride, which was a mixed microenvironment (Bhatt et al., 2016a).

### 2.2. Calibration procedure

The procedure involved an on-body calibration of the ExpoM-RF 64 for 15 frequency bands (in contrast to previous studies where no on-body calibration was included). The frequency bands calibrated were Digital Video Broadcasting-Terrestrial (DVB-T), 800 MHz downlink (DL) and uplink (UL), 900 MHz UL and DL, 1800 MHz UL and DL, Digital Enhanced Cordless Telecommunications (DECT), 1900 MHz UL and 2100 MHz DL, Industrial, Scientific and Medical (ISM) 2.4 GHz , 2600 MHz UL and DL, Worldwide Interoperability for Microwave Access (WiMax) 3.5 GHz and ISM 5.8 GHz. The central frequency levels calibrated were: 630 MHz (DVB-T), 806 MHz (DL), 847 MHz (UL), 897.5 MHz (900UL), 942.5 MHz (900 DL), 1747.5 MHz (1800 UL), 1842.5 MHz (1800 DL), 1890 MHz (DECT), 1950 MHz (UL), 2140 MHz (DL), 2442.5 MHz (ISM 2.4 GHz), 2535 MHz (2600 UL), 2655 MHz (2600 DL), 3500 MHz (WiMax 3.5 GHz) and 5512.5 MHz (ISM 5.8 GHz). Table B1 lists the different studied frequency bands and their frequency ranges. The personal exposure measured in this study should be interpreted as being frequency-band-specific and not attributed to a certain communication technology. The ExpoM-RF 40 was calibrated only for 900 DL MHz band. The FM radio band was not calibrated since the anechoic chamber used for the calibrations did not provide sufficient damping in this frequency band. We assumed that ExpoM-RF 40 would yield the same calibration responses as those of ExpoM-RF 64.

The ExpoM-RFs measure the incident frequency-band-specific electric field strengths ($E_{inc}$). The exposimeter(s), when worn on the body during measurements, register the electric field strengths on the body ($E_{body}$) (Bolte et al., 2011; Thielens et al., 2015a). Therefore, on-body calibration measurements are required in order to assess the relationship between $E_{inc}$ and $E_{body}$. The subject (a 35-year-old male; height 163 cm and weight 60 kg) participated in the on-body calibration in order to perform the subsequent field measurements (Fig. 1a). The on-body calibration procedure is discussed in detail elsewhere (Bhatt et al., 2016a). The calibration procedure was executed in a fully anechoic chamber following the procedure described in Thielens et al. (2015a); Bhatt et al. (2016a) (see also Appendix B).

### 2.3. Exposure assessment

Exposimeters were simultaneously employed in data collection across the microenvironments. Using traveler's money belts, the ExpoM-RF 64 and the ExpoM-RF 40 were attached to the left and right sides of the subject's hips (Fig. 1b). Both ExpoM-RFs were switched on and switched off simultaneously to synchronize the start and the end of the measurements. The root mean square (RMS) electric field strengths measured by the ExpoM RFs have been denoted as ($E_{rms}$), in V/m. The lower limits of detection (LOD)
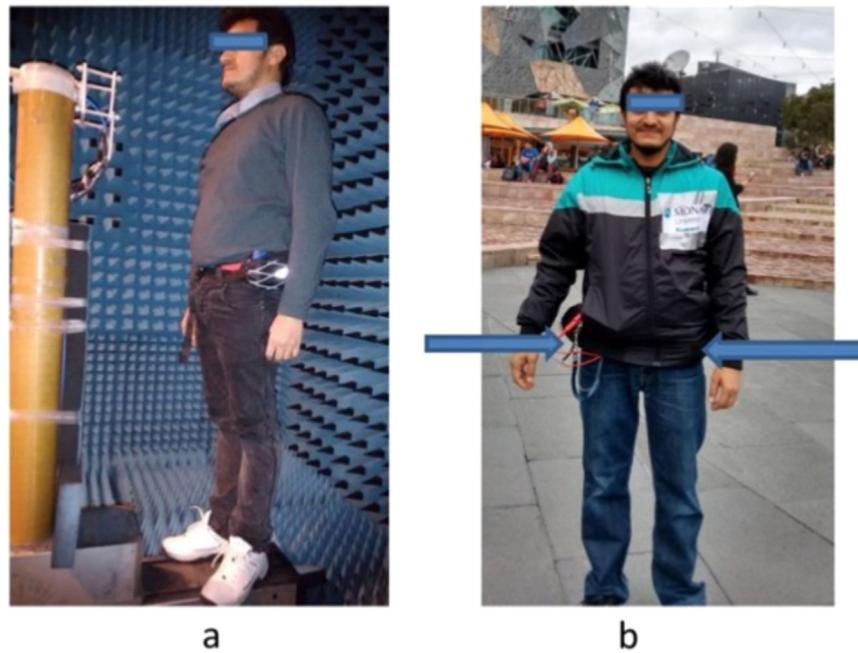
**Fig. 1.** The subject performing an on-body calibration of the ExpoM-RFs 64 in Ghent (a), and exposure measurement at a site in Melbourne using the on-body calibrated exposimeters (b) [arrows showing the locations of the ExpoM-RFs].

for each band of the ExpoM- RFs are: 20 mV/m (FM radio), 50 mV/m (ISM 5.8 GHz), 3 mV/m (2600 UL, DL and WiMax), and 5 mV/m (for the remaining frequencies). The upper LOD is 6 V/m in all frequency bands. The detection range of the ExpoM-RFs, with on-body calibration, is the value listed above, divided by the corresponding on-body response in the respective frequency bands. A light jacket worn by the subject covered both exposimeters while performing the measurements (Fig. 1b). The subject did not have any metal objects attached to his body during data collection.

All measurements were performed during the daytime (9:45 am–6:00 pm) or evening (6:00 pm–11:00 pm) on weekdays, except those of residential indoor and residential outdoor (rural/suburban) in Belgium, which were performed during the weekends (2:30–2:45 pm and 11:00–11:15 pm respectively). Each measurement duration was 15 min per microenvironment. A similar measurement duration were employed in the personal exposure monitoring by Urbinello et al., (2014a, 2014b). A smartphone watch, in flight mode, was used to monitor measurement time. The measurement intervals for the ExpoM-RFs were chosen to be 3 s (Bhatt et al., 2016a). Two ExpoM-RFs collected a total of 600 samples (300 each) per measurement for each microenvironment. Information on activities undertaken during data collection and descriptions of the microenvironments were recorded in a diary.

Twenty three microenvironmental measurements (13 in Australia and 10 in Belgium) were performed twice to evaluate exposure variability during the first and second measurements. We attempted to obtain as much spatio-temporal matching as possible for the repeated microenvironments. Spatial matching of the stationary microenvironmental measurements was ensured by walking across the same area/route and towards the same direction. However, in the case of city center (Belgium), the measurements were performed across the same urban area, but involved walking along a different route. For the 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.

### 2.4. Data processing and statistical analysis

The analysis commenced with an assessment of the censored exposure data ($E_{rms}$) falling below the lower detection limit (LODs) in the respective frequency bands for each microenvironment. A Shapiro-Wilk test was performed on the untransformed and log-transformed data to evaluate normality. Furthermore, visual inspection of histograms and the normal Q-Q plots was also carried out.

We used the substitution approach in order to estimate summary statistics from the measured data. This is an accepted method in the science of environmental exposure assessment (Hewett & Ganser, 2010). All left censored data (i.e. the data below LODs) were replaced with their frequency-specific respective values of LOD/$\sqrt{2}$ (Ganser and Hewett, 2010; Hewett and Ganser, 2007). In ISM 5.8 GHz band (of the ExpoM-RF 64 data), numerous values < LOD (non-zero) and zero values were recorded. We replaced only the non-zero values < LOD with LOD/$\sqrt{2}$. The ExpoM-RF 64 measurements < 20 mV/m in the ISM 5.8 GHz band were automatically set to zero as those values were most likely the result of crosstalk. For the ISM 5.8 GHz data of the ExpoM-RF 40, we set all values < 20 mV/m as zero and all the non-zero values < LOD with LOD/$\sqrt{2}$. The values below LODs of 2600 MHz DL and UL, and WiMax 3.5 GHz bands were replaced with zeros for the measurements of the microenvironments that were situated in the areas not covered by these networks (Radio Frequency National Site Archive, 2016). All 2600 MHz (DL and UL) data of the microenvironments in Belgium, and those of residential outdoor and residential indoor (rural/suburban) in Australia were set to zero. In addition, the data of ISM 5.8 GHz for the latter microenvironments in Australia, and those of WiMax 3.5 for the microenvironments located in rural/suburban regions of Belgium were also set to zero. Similarly, the WiMax 3.5 GHz and ISM 5.8 data of car (rural/suburban) in Australia was set to zero. In the case of mountain/forest (rural) in Australia, the data below the LODs of 900 MHz DL,

**Table 1**
The results of the on-body calibration of ExpoM-RF 64 attached to the left lateral hip of the subject as shown in Fig. 1.

| Frequency bands | ExpoM-RF 64 | | Geometric mean response (two ExpoM-RFs) | |
|---|---|---|---|---|
| | $R$ | $PI_{50}$ | $R_{gm}$ | $PI_{50}$ |
| DVB-T (470–790 MHz) | 0.48±0.004 | 8.6±0.032 | 0.46 ±0.002 | 4.9 ±0.047 |
| 800 UL (832–862 MHz) | 0.58±0.004 | 7.3±0.062 | 0.54 ±0.002 | 2.2±0.030 |
| 800 DL (791–821 MHz) | 0.47±0.002 | 7.3±0.021 | 0.46±0.001 | 2.1±0.006 |
| 900 UL (880–915 MHz) | 0.53±0.001 | 6.3±0.043 | 0.50±0.001 | 1.8±0.018 |
| 900 DL (925–960 MHz) | 0.44±0.0005 | 7.8±0.049 | 0.41±0.0006 | 1.3±0.011 |
| 1800 UL (1710–1785 MHz) | 0.55 ±0.003 | 9.8±0.034 | 0.47±0.001 | 2.9±0.026 |
| 1800 DL (1805–1880 MHz) | 0.43 ±0.002 | 7.9±0.060 | 0.40±0.002 | 5.1±0.020 |
| DECT (1880–1900 MHz) | 0.49±0.001 | 9.0±0.074 | 0.46 ±0.001 | 3.4 ±0.014 |
| 1900 UL (1920–1980 MHz) | 0.73 ±0.002 | 7.8±0.056 | 0.62 ±0.001 | 6.4±0.009 |
| 2100 DL (2110–2170 MHz) | 0.72±0.0005 | 8.7±0.056 | 0.57±0.0005 | 6.2 ±0.013 |
| ISM 2.4 (2400–2485 MHz) | 0.99 ±0.004 | 10 ±0.019 | 0.99±0.0008 | 3.1 ±0.056 |
| 2600 UL (2500–2570 MHz) | 1.3±0.004 | 10 ±0.043 | 0.91±0.0004 | 7.2 ±0.020 |
| 2600 DL (2620–2690 MHz) | 1.1 ±0.002 | 12 ±0.033 | 0.71 ±0.001 | 8.2 ±0.038 |
| WiMAX 3.5 (3400–3600 MHz) | 0.89 ±0.001 | 8.9±0.046 | 0.64±0.0006 | 4.7 ±0.014 |
| ISM 5.8 (5150–5875 MHz) | 3.1 ±0.005 | 8.4±0.051 | 2.6 ±0.012 | 5.7 ±0.032 |

DVB-T: Digital Video Broadcasting–Terrestrial, DL: Downlink, DECT: Digital Enhanced Cordless Telecommunications, ISM: Industrial, Scientific and Medical UL: Uplink, WiMAX: Worldwide Interoperability for Microwave Access, $R$: response ($E_{body}/E_{inc}$), $PI_{50}$: 50% prediction interval (in dB), $R_{gm}$: geometric mean response of two ExpoM-RFs

900 MHz UL, DVB-T, and FM Radio were substituted by their respective LOD/$\sqrt{2}$, whereas all data for the remaining bands were set to zero.

Geometric means of the electric field signals ($E_{rms}$) measured with two ExpoM-RFs were calculated within the selected sample intervals using the formula; *Geometric mean*=($E_{ExpoM-RF40} \times E_{ExpoM-RF64}$)$^{1/2}$/$R_{gm}$ (Bhatt et al., 2016a), where $R_{gm}$ is the geometric mean response of two ExpoM-RFs (see Table 1). As Table 1 demonstrates the geometric averaging leads to a lower prediction interval for the measured $E_{rms}$ values. Neubauer et al. (2008) suggested that frequency-specific calibration factor(s) should be applied while estimating RF-EMF exposures, because RF-EMF exposures close to the human body are otherwise underestimated, which depends on the dimension of the human body, positions of the body-worn exposimeter(s) and frequency bands. We have not reported the summary statistics for individual exposures measured by the ExpoM-RF. However, the frequency-specific estimated median exposures provided by the individual ExpoM-RFs across all microenvironments of each country were used to evaluate the correlation between ExpoM-RF 40 and ExpoM-RF 64. The median exposure values obtained for 19 microenvironments with ExpoM-RF 64 (n=19) and ExpoM-RF 40 (n=19) per frequency band in both countries were used to perform country-specific Spearman's rank correlation analysis. Furthermore, we also used median exposure levels measured with the ExpoM-RF 64 (without taking on-body calibration factors into account) across the 19 microenvironments in each country to compare the levels to those obtained with the concurrent use of the ExpoM-RF 64 and the ExpoM-RF 40. This would allow us to have a comparison between the exposure levels obtained with the use of a single non-on-body calibrated exposimeter (such as most personal exposimetry studies) and those obtained with the use of two on-body calibrated exposimeters (current study).

Summary statistics (mean, median, 25th, 75th and 95th percentiles) of personal exposure across the measured bands were then calculated for all microenvironments in Australia and Belgium.

The total and frequency-specific median exposures across all measured microenvironments in both countries were obtained from the distributions of medians of the total and frequency-specific RF-EMF exposures, respectively. Furthermore, the statistics of personal exposure for each microenvironment were also calculated in terms of the four exposure categories: i) total exposure, which was equal to the square root sum of the 16 bands

$$\left( E^2_{rms\text{-}FM} + E^2_{rms\text{-}DVB\text{-}T} + E^2_{rms\text{-}800\,UL} + E^2_{rms\text{-}800\,DL} + E^2_{rms\text{-}900\,UL} + E^2_{rms\text{-}900\,DL} \right.$$
$$+ E^2_{rms\text{-}1800\,UL} + E^2_{rms\text{-}1800\,DL} + E^2_{rms\text{-}DECT} + E^2_{rms\text{-}2100\,UL} + E^2_{rms\text{-}2100\,DL}$$
$$\left. + E^2_{rms\text{-}ISM\,2.4} + E^2_{rms\text{-}2600\,UL} + E^2_{rms\text{-}2600\,DL} + E^2_{rms\text{-}WiMAX\,3.5} + E^2_{rms\text{-}ISM\,5.8} \right);$$

ii) mobile phone base station DLs exposure, the square root sum of all DL bands $\left( E^2_{rms\text{-}800\,DL} + E^2_{rms\text{-}900\,DL} + E^2_{rms\text{-}1800\,DL} + E^2_{rms\text{-}2100\,DL} + E^2_{rms\text{-}2600\,DL} \right)$; iii) mobile phone base station UL exposure, the square root sum of all UL bands $\left( E^2_{rms\text{-}800\,UL} + E^2_{rms\text{-}900\,UL} + E^2_{rms\text{-}1800\,UL} + E^2_{rms\text{-}1900\,UL} + E^2_{rms\text{-}2600\,UL} \right)$, and iv) broadcast exposure, the square root sum of FM radio and DVB-T bands $\left( E^2_{rms\text{-}FM} + E^2_{rms\text{-}DVB\text{-}T} \right)$. The total personal exposures were compared across 34 similar microenvironments (17 in each country). Four microenvironments excluded from the comparison were: subway station/ride (urban), mountain/forest (rural) in Australia, and bicycle (rural/suburban), and car (rural/suburban) in Belgium. These were excluded because comparable corresponding microenvironments in the other country were not measured.

Wilcoxon rank sum tests were performed to: i) examine whether the exposures across the matched microenvironments in Australia and Belgium were different, ii) assess the exposure variability during the repeated measurements of a total of 20 microenvironments – Australia (n=13) and Belgium (n=7), iii) to evaluate if total, total DL, total UL and total broadcast median exposures across urban and rural/suburban microenvironments, as well as mobile and stationary microenvironments were different, and iv) to examine the difference between indoor and outdoor ISM 2.4 exposures. Furthermore, Spearman's rank correlation analysis was performed to examine the correlations between the median exposures of the compared microenvironments (n=17) in the two countries.

For all statistical tests, p < 0.05 (two sided) was considered as statistically significant. Data analysis was carried out with STATA ver13.1 (StataCorp, College Station, TX, USA).

## 3. Results

### 3.1. Calibration of the exposimeters

Table 1 shows the results of the on-body calibration of the ExpoM-RF 64 attached to the left lateral hip of the subject as indicated in Fig. 1. The response and 50% prediction interval for each band are denoted by $R$ and $PI_{50}$, respectively. The calculated geometric mean responses are denoted by $R_{gm}$.

Table B1 (Appendix B) shows the measured cross-talk of Ex-poM-RF 64 on the body of the calibrated subject. The cross-talk was determined using only the central frequencies of the bands. The cross-talk matrix was diagonal dominant and had a very small amount of off-body elements which were relatively high. The cross-talk of DECT induced in the 1800 DL band was relatively large (approximately half the value of the response) and the cross-talk of WiMAX 3.5 induced in the ISM 5.8 was relatively large as well, although less important since WiMAX was less common (see Table 1). The ISM 5.8 band generally suffered the most from cross-talk. Similarly, DVB-T induced most cross-talk in other frequency bands, since it was the lowest frequency band. Table B2 (Appendix B) lists the cross-talk matrix measured in the free space. The matrix was diagonal-dominant upper, central and lower frequencies.

## 3.2. Data characteristics

The measured exposure data of both exposimeters demonstrated varying degrees of censoring (Table A1, Appendix A), depending upon the type of frequency band and microenvironment. The amount of censoring also varied between ExpoM-RF 40 and ExpoM-RF 64 measured data at the same microenvironment. Of all frequency-specific microenviromental measurements, 47% of the data in Australia and 50% of the data in Belgium had 50% or more censored data, when measured with both ExpoM-RFs. The proportion of censoring across the measured frequency bands was much higher for the measurements performed at suburban and rural microenvironments compared to those at urban microenvironments. In general, the three frequency bands demonstrating the least proportion of censoring in both countries were: 900 MHz DL, 2100 MHz DL and ISM 2.4 GHz. The bands of 800 UL, 1800 UL, 1900 MHz UL, WiMAX 3.5 and ISM 5.8 in both countries, plus 2600 UL and 2600 DL in Australia, were amongst those demonstrating highest proportions of censoring.

Of all frequency band-specific microenvironmental measurements falling above the LODs, only 11% of the data in Australia and 18% of the data in Belgium followed lognormal distributions. Overall, the correlation of frequency-specific estimated median exposure levels measured with ExpoM-RF 40 and ExpoM-RF 64, from all microenvironments in both countries, showed high to very high positive correlations: Spearman rank correlation coefficients ($r_s$), 0.84–1 (Australia) and 0.72–0.99 (Belgium).

## 3.3. Descriptive statistics

Personal RF-EMF exposure across the measured frequency bands of all microenvironments in Australia and Belgium are summarized in Table 2 in terms of mean, median, 25th, 75th, and 95th percentiles. The five exposure sources providing the highest median exposures in Australia were: 1800 MHz DL, 900 MHz DL and 900 MHz UL (0.07 V/m); 2100 MHz DL (0.04 V/m); DECT and DVB-T (0.02 V/m). Similarly, 900 MHz DL (0.11 V/m), 2100 MHz DL (0.07 V/m), 1800 MHz DL (0.06 V/m), DVB-T and FM radio (0.05 V/m) provided the five highest median exposures in Belgium.

Table 2 also compares the exposure levels measured with a single non-on-body calibrated exposimeter (ExpoM-RF 64) vs those with two concurrently employed on-body calibrated exposimeters (ExpoM-RF 64 and ExpoM-RF 40). The exposures measured with the two exposimeters were nearly 2–3 times higher than those measured with the single exposimeter. However, this was not the case for FM, ISM 2.4 GHz, 2600 UL and DL, where the exposure levels were of similar values.

Table 3 summarizes the descriptive statistics (mean, median, 25th, 75th, and 95th percentiles) of the personal RF-EMF exposure levels for total, total downlink, total uplink and total broadcast across different microenvironments in Australia and Belgium.

In Australia, the five highest total median exposure levels measured were: city center (4.33 V/m), residential outdoor (urban) (0.75 V/m), park (0.75 V/m), bicycle (urban) (0.71 V/m), and train station (0.48 V/m). Likewise, the five lowest total median exposure levels measured were: mountain forest (rural) (0.02 V/m), shopping center (urban) (0.04 V/m), residential indoor (rural/suburban) (0.05 V/m), car (urban/suburban) (0.05 V/m), and office indoor (urban) (0.06 V/m).

In Belgium, the five highest total median exposures measured were: tram station (1.95 V/m), city center (0.95 V/m), park (0.90 V/m), residential outdoor (urban) (0.87 V/m), and library (0.77 V/m). Similarly, the five lowest total median exposure levels measured were: residential indoor (rural/suburban) (0.04 V/m), residential outdoor (rural/suburban) (0.07 V/m), office indoor (urban) (0.10 V/m), car (rural/suburban) (0.11 V/m), and bicycle (rural/suburban) (0.12 V/m).

## 3.4. Comparison of microenvironmental exposures

Of 17 microenvironmental total exposures measured in each country, only eight microenvironments in Belgium followed lognormal distributions, whereas six followed lognormal and two normal distributions in Australia. The other microenvironmental total exposure data followed neither lognormal nor normal distributions.

The Wilcoxon rank sum tests showed that total exposure for nine microenvironments in Australia were lower than the exposure across the corresponding microenvironments in Belgium ($p < 0.05$) (Table 4). However, the exposure in Australia was found to be higher than the corresponding exposure in Belgium for the five microenvironments ($p < 0.05$) – city center, tram, train, residential outdoor (rural/suburban), and residential indoor (rural/suburban) and the airport. Furthermore, the total exposure levels for the bicycle (urban) and bus microenvironments in Australia and Belgium did not show any significant difference. Although the train station microenvironment in Australia provided higher exposure than that in Belgium, the difference was not statistically significant ($p = 0.32$).

The microenvironmental comparisons for total and total DL median exposures in both countries showed strong positive correlations: $r_s = 0.74$ ($p = 0.006$) for total, and $r_s = 0.73$ ($p = 0.0007$) for total DL exposures. Furthermore, there were no significant or weak correlations for the total UL and total broadcast exposures ($r_s = 0.086$, $p = 0.74$ for total UL, and $r_s = 0.46$, $p = 0.06$ for total broadcast).

In Australia, total, total DL, and total UL exposures across urban microenvironments were higher than those across rural/suburban microenvironments ($p = 0.03$). However, there was no difference between urban and rural/suburban microenviromental exposures for total broadcast ($p = 0.28$). Nor were there significant differences in total, total DL, total UL and total broadcast exposures between mobile and stationary microenvironments ($p = 0.64$–$0.90$).

In Belgium, total, total DL and total broadcast exposures in urban microenvironments were higher than those in rural/suburban microenvironments ($p = 0.006$ for total, $p = 0.02$ for total DL, and 0.01 for total broadcast). Whereas there was no difference in the total UL exposure in urban and that in rural/suburban microenvironments ($p = 0.09$). There were no significant

**Table 2**
Summary of the frequency-specific and total personal RF-EMF exposure levels of all microenvironments in Australia (n=19) and Belgium (n=19) [single non-on-body calibrated ExpoM-RF 64 data vs concurrently used on-body calibrated ExpoM-RF 64 and ExpoM-RF 40 data].

| Frequency bands | Summary statistics (mean, median, 25th, 75th and 95th percentiles) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Australia | | | | Belgium | | | |
| | $E_{rms}$ (with a single exposimeter) | | $E_{rms}$ (with two exposimeters) | | $E_{rms}$ (with a single exposimeter) | | $E_{rms}$ (with two exposimeters) | |
| | Mean (SD) | median (25th, 75th and 95th percentiles) | Mean (SD) | median (25th, 75th and 95th percentiles) | Mean (SD) | median (25th, 75th and 95th percentiles) | Mean (SD) | median (25th, 75th and 95th percentiles) |
| FM radio (87.5–108 MHz) | 0.02 (0.03) | 0.01 (0.01, 0.03, 0.14) | 0.03 (0.03) | 0.01 (0.01, 0.03, 0.13) | 0.05 (0.03) | 0.04 (0.01, 0.08, 0.10) | 0.05 (0.04) | 0.05 (0.01, 0.09, 0.12) |
| DVB-T (470–790 MHz) | 0.03 (0.06) | 0.007 (0.003, 0.04, 0.25) | 0.08 (0.15) | 0.02 (0.007, 0.08, 0.69) | 0.03 (0.03) | 0.02 (0.003, 0.05, 0.09) | 0.07 (0.07) | 0.05 (0.007, 0.11, 0.23) |
| 800 UL (832–862 MHz) | 0.009 (0.01) | 0.003 (0.005, 0.01, 0.05) | 0.02 (0.02) | 0.009 (0.006, 0.02, 0.10) | 0.003 (0.005) | 0.003 (0.003, 0.003, 0.005) | 0.007 (0.001) | 0.006 (0.006, 0.006, 0.01) |
| 800 DL (791–821 MHz) | 0.005 (0.002) | 0.003 (0.003, 0.006, 0.01) | 0.009 (0.004) | 0.007 (0.007, 0.01, 0.02) | 0.05 (0.07) | 0.02 (0.008, 0.09, 0.23) | 0.10 (0.14) | 0.03 (0.01, 0.19, 0.47) |
| 900UL (880–915 MHz) | 0.04 (0.03) | 0.03 (0.008, 0.06, 0.12) | 0.08 (0.07) | 0.07 (0.01, 0.11, 0.26) | 0.008 (0.009) | 0.003 (0.003, 0.005, 0.03) | 0.01 (0.01) | 0.007 (0.007, 0.01, 0.05) |
| 900 DL (925–960 MHz) | 0.08 (0.12) | 0.03 (0.01, 0.12, 0.56) | 0.24 (0.40) | 0.07 (0.03, 0.31, 1.78) | 0.13 (0.17) | 0.07 (0.03, 0.24, 0.71) | 0.30 (0.35) | 0.11 (0.06, 0.54, 1.37) |
| 1800 UL (1710–1785 MHz) | 0.005 (0.005) | 0.003 (0.003, 0.003, 0.02) | 0.01 (0.01) | 0.007 (0.007, 0.01, 0.06) | 0.005 (0.002) | 0.003 (0.003, 0.005, 0.01) | 0.01 (0.007) | 0.007 (0.007, 0.009, 0.03) |
| 1800 DL (1805–1880 MHz) | 0.10 (0.21) | 0.03 (0.01, 0.11, 0.93) | 0.27 (0.58) | 0.08 (0.03, 0.28, 2.62) | 0.06 (0.08) | 0.02 (0.005, 0.09, 0.37) | 0.14 (0.21) | 0.06 (0.01, 0.23, 0.87) |
| DECT (1880–1900 MHz) | 0.03 (0.05) | 0.008 (0.003, 0.03, 0.24) | 0.07 (0.14) | 0.02 (0.007, 0.06, 0.61) | 0.02 (0.04) | 0.01 (0.003, 0.02, 0.18) | 0.05 (0.08) | 0.03 (0.007, 0.05, 0.37) |
| 1900 UL (1920–1980 MHz) | 0.007 (0.01) | 0.002 (0.002, 0.003, 0.06) | 0.01 (0.02) | 0.003 (0.003, 0.006, 0.10) | 0.003 (0.003) | 0.002 (0.002, 0.003, 0.01) | 0.005 (0.005) | 0.003 (0.003, 0.007, 0.02) |
| 2100 DL (2110–2170 MHz) | 0.09 (0.25) | 0.02 (0.004, 0.08, 1.13) | 0.17 (0.49) | 0.04 (0.007, 0.12, 2.18) | 0.07 (0.09) | 0.03 (0.008, 0.11, 0.39) | 0.12 (0.16) | 0.07 (0.01, 0.20, 0.68) |
| ISM 2.4 (2400–2485 MHz) | 0.02 (0.02) | 0.01 (0.01, 0.02, 0.06) | 0.01 (0.01) | 0.01 (0.008, 0.01, 0.06) | 0.02 (0.01) | 0.02 (0.01, 0.02, 0.05) | 0.02 (0.01) | 0.02 (0.008, 0.02, 0.04) |
| 2600 UL (2500–2570 MHz) | 0.002 (0.001) | 0.002 (0.002, 0.002, 0.006) | 0.002 (0.001) | 0.002 (0.002, 0.002, 0.006) | 0 (0) | 0 (0, 0, 0) | 0 (0) | 0 (0, 0, 0) |
| 2600 DL (2620–2690 MHz) | 0.03 (0.07) | 0.002 (0.002, 0.02, 0.33) | 0.04 (0.11) | 0.003 (0.003, 0.03, 0.47) | 0 (0) | 0 (0, 0, 0) | 0 (0) | 0 (0, 0, 0) |
| WiMAX 3.5 (3400–3600 MHz) | 0.002 (0.002) | 0.002 (0.002, 0.02, 0.009) | 0.003 (0.003) | 0.003 (0.003, 0.003, 0.01) | 0.003 (0.006) | 0.002 (0.002, 0.002, 0.02) | 0.003 (0.004) | 0.003 (0, 0.003, 0.02) |
| ISM 5.8 (5150–5875 MHz) | 0.02 (0.06) | 0 (0, 0.03, 0.26) | 0.01 (0.02) | 0 (0, 0.01, 0.11) | 0.02 (0.02) | 0 (0, 0.03, 0.08) | 0.0006 (0.008) | 0 (0, 0.01, 0.003) |
| Total | 0.20 (0.36) | 0.10 (0.03, 0.19, 1.67) | 0.52 (0.95) | 0.38 (0.06, 0.48, 4.34) | 0.21 (0.22) | 0.12 (0.07, 0.33, 0.95) | 0.46 (0.47) | 0.30 (0.12, 0.77, 1.95) |

Abbreviations: DVB-T: Digital Video Broadcasting–Terrestrial, DL: Downlink, DECT: Digital Enhanced Cordless Telecommunications, FM: Frequency Modulated, ISM: Industrial, Scientific and Medical, SD: Standard deviation, UL: Uplink, WiMAX: Worldwide Interoperability for Microwave Access; [†]majority of the measured data have replaced values of the LOD/$\sqrt{2}$ for these frequency bands

**Table 3**

Personal total, total downlink, total uplink and total broadcast exposures ($E_{rms}$) across various microenvironments in Australia (n=19) and Belgium (n=19).

| Microenvironments | Total (V/m) | | | Total downlink (V/m) | | | Total uplinks (V/m) | | | Total broadcast (V/m) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Mean (SD) | Median | 25th, 75th & 95th percentiles | Mean (SD) | Median | 25th, 75th & 95th percentiles | Mean (SD) | Median | 25th, 75th & 95th percentiles | Mean (SD) | Median | 25th, 75th & 95th percentiles |
| **Residential outdoor (urban)** | | | | | | | | | | | | |
| Australia | 0.93 (0.62) | 0.75 | 0.41, 1.32, 2.05 | 0.90 (0.61) | 0.70 | 0.39, 1.28, 2.01 | 0.17 (0.10) | 0.14 | 0.10, 0.22, 0.36 | 0.05 (0.02) | 0.04 | 0.03, 0.05, 0.08 |
| Belgium | 0.92 (0.40) | 0.87 | 0.70, 1.13, 1.64 | 0.91 (0.40) | 0.86 | 0.68, 1.12, 1.64 | 0.01 (0.004) | 0.01 | 0.01, 0.01, 0.02 | 0.11 (0.04) | 0.11 | 0.09, 0.14, 0.18 |
| **Residential indoor (urban)** | | | | | | | | | | | | |
| Australia | 0.15 (0.06) | 0.13 | 0.10, 0.20, 0.26 | 0.14 (0.06) | 0.11 | 0.09, 0.19, 0.24 | 0.05 (0.01) | 0.04 | 0.04, 0.06, 0.08 | 0.02 (0.004) | 0.02 | 0.02, 0.02, 0.03 |
| Belgium | 0.24 (0.08) | 0.25 | 0.20, 0.30, 0.37 | 0.23 (0.08) | 0.23 | 0.18, 0.28, 0.35 | 0.05 (0.01) | 0.01 | 0.01, 0.03, 0.04 | 0.07 (0.03) | 0.07 | 0.05, 0.08, 0.12 |
| **Office indoor (urban)** | | | | | | | | | | | | |
| Australia | 0.07 (0.02) | 0.06 | 0.05, 0.09, 0.10 | 0.05 (0.02) | 0.04 | 0.03, 0.06, 0.07 | 0.02 (0.01) | 0.02 | 0.02, 0.03, 0.05 | 0.03 (0.01) | 0.02 | 0.01, 0.04, 0.05 |
| Belgium | 0.11 (0.06) | 0.10 | 0.074, 0.14, 0.23 | 0.07 (0.03) | 0.061 | 0.05, 0.08, 0.15 | 0.03 (0.02) | 0.02 | 0.01, 0.03, 0.08 | 0.02 (0.004) | 0.01 | 0.01, 0.02, 0.02 |
| **Park (urban)** | | | | | | | | | | | | |
| Australia | 0.75 (0.45) | 0.75 | 0.38, 0.95, 1.30 | 0.70 (0.44) | 0.70 | 0.34, 0.90, 1.26 | 0.19 (0.10) | 0.17 | 0.11, 0.25, 0.41 | 0.08 (0.03) | 0.08 | 0.06, 0.10, 0.14 |
| Belgium | 0.96 (0.45) | 0.90 | 0.59, 1.18, 1.82 | 0.90 (0.46) | 0.85 | 0.54, 1.13, 1.77 | 0.01 (0.004) | 0.01 | 0.01, 0.01, 0.02 | 0.25 (0.09) | 0.26 | 0.20, 0.31, 0.39 |
| **City center** | | | | | | | | | | | | |
| Australia | 4.50 (1.31) | 4.33 | 3.55, 5.34, 6.84 | 4.36 (1.31) | 4.20 | 3.42, 5.18, 6.62 | 0.31 (0.11) | 0.29 | 0.24, 0.35, 0.55 | 0.73 (0.23) | 0.69 | 0.56, 0.86, 1.21 |
| Belgium | 1.16 (0.70) | 0.95 | 0.58, 1.65, 2.42 | 1.12 (0.70) | 0.93 | 0.54, 1.61, 2.37 | 0.03 (0.02) | 0.02 | 0.02, 0.03, 0.06 | 0.20 (0.06) | 0.02 | 0.16, 0.23, 0.30 |
| **Library (urban)** | | | | | | | | | | | | |
| Australia | 0.11 (0.03) | 0.10 | 0.09, 0.12, 0.15 | 0.09 (0.02) | 0.09 | 0.07, 0.10, 0.13 | 0.04 (0.01) | 0.04 | 0.04, 0.05, 0.06 | 0.02 (0.002) | 0.02 | 0.01, 0.02, 0.02 |
| [a]Belgium | 0.99 (0.51) | 0.77 | 0.63, 1.22, 2.02 | 0.94 (0.47) | 0.74 | 0.60, 1.18, 1.92 | 0.01 (0.001) | 0.01 | 0.01, 0.01, 0.01 | 0.14 (0.04) | 0.14 | 0.11, 0.16, 0.20 |
| **Shopping center (urban)** | | | | | | | | | | | | |
| Australia | 0.06 (0.05) | 0.04 | 0.04, 0.05, 0.14 | 0.04 (0.04) | 0.02 | 0.02, 0.03, 0.09 | 0.03 (0.02) | 0.02 | 0.01, 0.03, 0.06 | 0.02 (0.02) | 0.02 | 0.01, 0.02, 0.06 |
| [a]Belgium | 0.14 (0.05) | 0.13 | 0.10, 0.17, 0.24 | 0.08 (0.05) | 0.07 | 0.05, 0.09, 0.16 | 0.07 (0.05) | 0.06 | 0.04, 0.08, 0.14 | 0.06 (0.04) | 0.04 | 0.03, 0.07, 0.13 |
| **Train station (urban)** | | | | | | | | | | | | |
| Australia | 0.47 (0.13) | 0.48 | 0.39, 0.55, 0.64 | 0.40 (0.11) | 0.41 | 0.32, 0.47, 0.56 | 0.08 (0.04) | 0.07 | 0.06, 0.09, 0.16 | 0.10 (0.08) | 0.08 | 0.07, 0.11, 0.18 |
| [a]Belgium | 0.89 (1.14) | 0.30 | 0.13, 1.14, 3.29 | 0.82 (1.12) | 0.11 | 0.07, 1.12, 3.15 | 0.06 (0.04) | 0.05 | 0.03, 0.08, 0.14 | 0.11 (0.06) | 0.12 | 0.08, 0.14, 0.18 |
| **Train** | | | | | | | | | | | | |
| Australia | 0.42 (0.23) | 0.38 | 0.25, 0.54, 0.8 | 0.17 (0.14) | 0.13 | 0.06, 0.23, 0.49 | 0.32 (0.26) | 0.02 | 0.11, 0.45, 0.77 | 0.06 (0.06) | 0.05 | 0.02, 0.08, 0.19 |
| Belgium | 0.34 (0.32) | 0.24 | 0.14, 0.40, 1.02 | 0.13 (0.10) | 0.11 | 0.05, 0.17, 0.32 | 0.25 (0.35) | 0.09 | 0.03, 0.32, 1.02 | 0.05 (0.07) | 0.01 | 0.01, 0.04, 0.20 |
| **Tram station (urban)** | | | | | | | | | | | | |
| Australia | 0.44 (0.11) | 0.43 | 0.36, 0.51, 0.64 | 0.40 (0.10) | 0.40 | 0.32, 0.47, 0.60 | 0.11 (0.03) | 0.11 | 0.09, 0.13, 0.17 | 0.11 (0.03) | 0.11 | 0.09, 0.13, 0.16 |
| [a]Belgium | 1.97 (0.48) | 1.95 | 1.61, 2.32, 2.77 | 1.91 (0.46) | 1.91 | 1.58, 2.23, 2.69 | 0.02 (0.01) | 0.01 | 0.01, 0.02, 0.03 | 0.18 (0.04) | 0.17 | 0.15, 0.20, 0.24 |
| **Tram (urban)** | | | | | | | | | | | | |
| Australia | 0.62 (0.44) | 0.47 | 0.33, 0.78, 1.52 | 0.53 (0.46) | 0.39 | 0.19, 0.69, 1.47 | 0.17 (0.11) | 0.15 | 0.09, 0.23, 0.38 | 0.15 (0.08) | 0.12 | 0.09, 0.19, 0.30 |
| [a]Belgium | 0.53 (0.35) | 0.43 | 0.24, 0.75, 1.20 | 0.45 (0.38) | 0.33 | 0.14, 0.71, 1.18 | 0.04 (0.04) | 0.02 | 0.01, 0.05, 0.16 | 0.17 (0.11) | 0.15 | 0.11, 0.20, 0.37 |
| **Bus (urban)** | | | | | | | | | | | | |
| Australia | 0.45 (0.29) | 0.45 | 0.17, 0.65, 0.93 | 0.39 (0.27) | 0.40 | 0.12, 0.58, 0.82 | 0.15 (0.12) | 0.12 | 0.08, 0.19, 0.40 | 0.09 (0.06) | 0.08 | 0.04, 0.13 0.20 |
| [a]Belgium | 0.45 (0.28) | 0.41 | 0.22, 0.61, 1.01 | 0.33 (0.25) | 0.26 | 0.16, 0.45, 0.76 | 0.03 (0.03) | 0.02 | 0.01, 0.04, 0.10 | 0.25 (0.21) | 0.19 | 0.09, 0.36, 0.70 |
| **Subway station & ride (urban)** | | | | | | | | | | | | |
| [a]Australia | 0.43 (0.19) | 0.41 | 0.32, 0.54, 0.75 | 0.19 (0.11) | 0.20 | 0.09, 0.27, 0.40 | 0.21 (0.22) | 0.10 | 0.05, 0.32, 0.68 | 0.12 (0.08) | 0.12 | 0.04, 0.18, 0.24 |
| **Airport indoor** | | | | | | | | | | | | |
| [a]Australia | 0.27 (0.13) | 0.24 | 0.17, 0.35, 0.51 | 0.15 (0.16) | 0.05 | 0.04, 0.26, 0.47 | 0.16 (0.10) | 0.12 | 0.08, 0.21, 0.38 | 0.16 (0.10) | 0.01 | 0.01, 0.02, 0.11 |
| [a]Belgium | 0.17 (0.05) | 0.16 | 0.13, 0.20, 0.26 | 0.15 (0.05) | 0.14 | 0.11, 0.17, 0.24 | 0.06 (0.04) | 0.05 | 0.04, 0.08, 0.13 | 0.02 (0.003) | 0.01 | 0.01, 0.01, 0.02 |

**Table 3** (*continued*)

| Microenvironments | Total (V/m) | | | Total downlink (V/m) | | | Total uplinks (V/m) | | | Total broadcast (V/m) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Mean (SD) | Median | 25th, 75th & 95th percentiles | Mean (SD) | Median | 25th, 75th & 95th percentiles | Mean (SD) | Median | 25th, 75th & 95th percentiles | Mean (SD) | Median | 25th, 75th & 95th percentiles |
| Bicycle (urban) | | | | | | | | | | | | |
| Australia | 0.90 (0.65) | 0.71 | 0.40, 1.22, 2.34 | 0.82 (0.63) | 0.64 | 0.33, 1.14, 2.19 | 0.21 (0.17) | 0.14 | 0.09, 0.28, 0.55 | 0.21 (0.16) | 0.01 | 0.01, 0.02, 0.05 |
| [a]Belgium | 0.78 (0.30) | 0.73 | 0.57, 0.97, 1.33 | 0.74 (0.31) | 0.69 | 0.55, 0.93, 1.29 | 0.01 (0.02) | 0.01 | 0.01, 0.01, 0.02 | 0.02 (0.07) | 0.20 | 0.15, 0.25, 0.31 |
| Bicycle (rural/suburban) | | | | | | | | | | | | |
| [a]Belgium | 0.15 (0.09) | 0.12 | 0.09, 0.18, 0.36 | 0.15 (0.09) | 0.11 | 0.08, 0.17, 0.36 | 0.01 (0.002) | 0.01 | 0.01, 0.01, 0.01 | 0.02 (0.002) | 0.01 | 0.01, 0.01, 0.02 |
| Car (urban/suburban) Australia | 0.07 (0.06) | 0.05 | 0.03, 0.09, 0.22 | 0.06 (0.06) | 0.03 | 0.02, 0.06, 0.19 | 0.02 (0.02) | 0.01 | 0.01, 0.02, 0.07 | 0.02 (0.02) | 0.01 | 0.01, 0.02, 0.06 |
| Belgium | 0.40 (0.26) | 0.31 | 0.20, 0.54, 0.95 | 0.37 (0.26) | 0.29 | 0.18, 0.52, 0.92 | 0.01 (0.01) | 0.01 | 0.01, 0.01, 0.03 | 0.09 (0.06) | 0.08 | 0.06, 0.11, 0.22 |
| Car (rural/suburban) | | | | | | | | | | | | |
| [a]Belgium | 0.14 (0.11) | 0.11 | 0.05, 0.19, 0.35 | 0.12 (0.11) | 0.09 | 0.03, 0.18, 0.33 | 0.01 (0.007) | 0.01 | 0.01, 0.01, 0.01 | 0.02 (0.01) | 0.01 | 0.01, 0.01, 0.05 |
| Residential outdoor (rural/suburban) | | | | | | | | | | | | |
| Australia | 0.09 (0.02) | 0.10 | 0.08, 0.11, 0.12 | 0.08 (0.02) | 0.08 | 0.07, 0.09, 0.10 | 0.03 (0.008) | 0.03 | 0.02, 0.03, 0.04 | 0.04 (0.01) | 0.03 | 0.03, 0.04, 0.06 |
| Belgium | 0.07 (0.04) | 0.07 | 0.05, 0.09, 0.12 | 0.07 (0.03) | 0.06 | 0.04, 0.09, 0.12 | 0.01 (0.03) | 0.01 | 0.01, 0.01, 0.01 | 0.01 (0.001) | 0.01 | 0.01, 0.01, 0.02 |
| Residential indoor (rural/suburban) | | | | | | | | | | | | |
| [a]Australia | 0.05 (0.01) | 0.05 | 0.04, 0.05, 0.06 | 0.03 (0.002) | 0.03 | 0.03, 0.03, 0.03 | 0.01 (0.006) | 0.01 | 0.01, 0.01, 0.01 | 0.03 (0.01) | 0.03 | 0.02, 0.04, 0.05 |
| Belgium | 0.04 (0.03) | 0.04 | 0.03 0.04, 0.09 | 0.02 (0.001) | 0.02 | 0.02, 0.02, 0.02 | (0.005) | 0.01 | 0.01, 0.01, 0.01 | 0.01 (0.0002) | 0.01 | 0.01, 0.01, 0.01 |
| Mountain/forest (rural) | | | | | | | | | | | | |
| [a]Australia | 0.02 (0.0007) | 0.02 | 0.02, 0.02, 0.02 | 0.01 (0.0005) | 0.01 | 0.01, 0.02, 0.02 | 0.007 (0) | 0.007 | 0.007, 0.007, 0.007 | 0.007 (0) | 0.01 | 0.01, 0.01, 0.01 |

[a]Single measurement, SD: Standard deviation.

**Table 4**
Evaluation of the variability in total personal exposure (V/m) during the 1st ($m_1$) and 2nd measurements ($m_2$) in Australia (n=13) and Belgium (n=7).

| Microenvironments | Total exposure levels ($m_1$) [V/m] | | | Total exposure levels ($m_2$) [V/m] | | | [†]p values |
|---|---|---|---|---|---|---|---|
| | Mean (SD) | Median | 25th, 75th & 95th percentiles | Mean (SD) | Median | 25th, 75th & 95th percentiles | |
| **Residential outdoor (urban)** | | | | | | | |
| Australia | 1.06 (0.68) | 0.89 | 0.46, 1.57, 2.40 | 0.80 (0.52) | 0.67 | 0.38, 1.10, 1.68 | **< 0.001** |
| Belgium | 0.93 (0.37) | 0.90 | 0.73, 1.14, 1.56 | 0.91 (0.42) | 0.85 | 0.67, 1.13, 1.72 | 0.16 |
| **Residential indoor (urban)** | | | | | | | |
| Australia | 0.18 (0.05) | 0.19 | 0.13, 0.22, 0.27 | 0.12 (0.04) | 0.11 | 0.10, 0.12, 0.23 | **< 0.001** |
| Belgium | 0.20 (0.07) | 0.21 | 0.13, 0.25, 0.30 | 0.29 (0.08) | 0.30 | 0.25, 0.33, 0.41 | **< 0.001** |
| **Office indoor (urban)** | | | | | | | |
| Australia | 0.06 (0.02) | 0.06 | 0.05, 0.07, 0.10 | 0.07 (0.02) | 0.08 | 0.04, 0.09, 0.10 | 0.19 |
| Belgium | 0.13 (0.07) | 0.11 | 0.08, 0.16, 0.31 | 0.09 (0.04) | 0.08 | 0.06, 0.12, 0.16 | **< 0.001** |
| **Park (urban)** | | | | | | | |
| Australia | 0.69 (0.32) | 0.67 | 0.45, 0.89, 1.16 | 0.79 (0.52) | 0.79 | 0.35, 0.99, 1.43 | 0.05 |
| Belgium | 0.87 (0.36) | 0.80 | 0.56, 1.13, 1.54 | 1.07 (0.52) | 0.98 | 0.73, 1.25, 2.12 | **< 0.001** |
| **City center** | | | | | | | |
| Australia | 4.58 (1.30) | 4.39 | 3.61, 5.24, 7.13 | 4.38 (1.32) | 4.28 | 3.27, 5.51, 6.41 | 0.17 |
| **Library (urban)** | | | | | | | |
| Australia | 0.10 (0.02) | 0.10 | 0.09, 0.11, 0.14 | 0.11 (0.03) | 0.11 | 0.08, 0.13, 0.16 | 0.06 |
| **Train station (urban)** | | | | | | | |
| Australia | 0.50 (0.09) | 0.51 | 0.43, 0.57, 0.62 | 0.44 (0.15) | 0.43 | 0.32, 0.52, 0.65 | **< 0.001** |
| **Train** | | | | | | | |
| Australia | 0.48 (0.17) | 0.46 | 0.37, 0.59, 0.78 | 0.37 (0.27) | 0.28 | 0.20, 0.45, 0.84 | **< 0.001** |
| Belgium | 0.17 (0.09) | 0.14 | 0.10, 0.29, 0.36 | 0.50 (0.38) | 0.38 | 0.23, 0.60, 1.33 | **< 0.001** |
| **Tram station (urban)** | | | | | | | |
| Australia | 0.50 (0.10) | 0.49 | 0.43, 0.55, 0.67 | 0.38 (0.08) | 0.37 | 0.32, 0.43, 0.53 | **< 0.001** |
| **Tram (urban)** | | | | | | | |
| Australia | 0.59 (0.45) | 0.46 | 0.23, 0.73, 1.52 | 0.65 (0.42) | 0.49 | 0.38, 0.80, 1.56 | **< 0.001** |
| **Bicycle (urban)** | | | | | | | |
| Australia | 0.88 (0.66) | 0.74 | 0.33, 1.23, 2.28 | 0.93 (0.65) | 0.69 | 0.44, 1.22, 2.42 | **0.04** |
| **Bus (urban)** | | | | | | | |
| Australia | 0.43 (0.33) | 0.38 | 0.13, 0.67, 0.97 | 0.47 (0.24) | 0.50 | 0.25, 0.63, 0.89 | **0.004** |
| **Car (urban)** | | 0.28 | 0.17, 0.47, 0.83 | | 0.34 | 0.22, 0.58, 1.08 | **< 0.001** |
| **Residential indoor (rural/suburban)** | | | | | | | |
| Belgium | 0.04 (0.01) | 0.03 | 0.03, 0.04, 0.08 | 0.05 (0.03) | 0.04 | 0.03, 0.04, 0.10 | **< 0.001** |
| **Residential outdoor (rural/suburban)** | | | | | | | |
| Australia | 0.09 (0.02) | 0.09 | 0.08, 0.10, 0.12 | 0.10 (0.02) | 107 | 0.09, 0.11, 0.13 | **< 0.001** |
| Belgium | 0.08 (0.05) | 0.07 | 0.05, 0.10, 0.13 | 0.07 (0.02) | 0.06 | 0.05, 0.08, 0.11 | **0.002** |

[†]p values < 0.05 statistically significant different exposure levels, SD: Standard deviation

differences in total, total DL, total UL and total broadcast exposures between mobile and stationary microenvironments ($p=0.36$–0.96).

### 3.5. Assessment of the variability in exposures

Wilcoxon rank sum tests were undertaken to evaluate the repeated measurements of the RF-EMF exposure levels. The results have been tabulated in Table 4. Overall, half of the microenvironments (10 of 20 in both countries) showed that repeated measurements provided different total median exposure levels.

Of the 13 microenvironments repeated in Australia, nine showed statistically different total exposure levels at the first and second measurements ($p < 0.001$–0.04) (Table 4), whereas four did not show any significant difference ($p > 0.05$) between the exposure levels. For the tram and residential outdoor (rural/suburban) microenvironments, the total exposures during the two measurement sessions showed little difference, though the p values were statistically significant.

Of the seven microenvironments repeated in Belgium, six showed statistically different total exposure levels at the first and second measurements ($p < 0.001$–0.002). However, despite having significant p values, office indoor (urban), residential indoor, and residential outdoor (rural/suburban) provided a little difference in exposure between the first and second measurements. Residential outdoor (urban) did not show statistically significant variation in the exposure levels measured during the repeated measurements ($p=0.16$).

### 4. Discussion

We have evaluated far-field personal RF-EMF exposures across the different microenvironments in Australia and Belgium by employing two on-body calibrated exposimeters. Measurement of exposures in microenvironments allowed us to: i) identify typical exposure levels in the specific microenvironments, ii) monitor exposure trends across these

microenvironments over time, and iii) help characterize personal exposure assuming a person occupies a specific microenvironment for a certain amount of time (Dürrenberger et al., 2014). Since most of our exposure data characterized nonnormal or non-lognormal distribution, we have preferred to present our results in terms of median and percentiles. Similar presentation of RF-EMF summary statistics have been provided elsewhere (e.g. Bhatt et al., 2016a; Najera et al., 2016). The use of two exposimeters to assess exposure in this study demonstrated that the exposimeters may measure different amounts of RF-EMF signals simultaneously whilst on the body. The proportion of detected signals was high for the mobile phone DL and Wi-Fi bands, which is due to the fact that these signals were relatively common across all microenvironments.

### 4.1. Exposure characteristics in Australia and Belgium

Our study found that mobile phone base downlink exposures contributed the largest share to total exposures (Table 3). Similar results have been reported elsewhere (e.g. Sagar et al., 2016; Urbinello et al., 2014c). The usage of mobile phones and degree of evolution of mobile phone network signals (e.g. Global System for Mobile communication 900 and 1800, Universal Mobile Telecommunications System, and Long-Term Evolution) in Australia and Belgium are not quite the same (International Telecommunication Union, 2010; Kumar, 2004; SpectrumMonitoring, 2016a, 2016b). This perhaps explains the different contribution of frequency band-specific exposures to total RF-EMF exposure in the two countries. We also demonstrated that the concurrent use of two on-body calibrated exposimeters provided the average exposure levels of 1.35 and 1.6 times higher in Australia and Belgium respectively, than those provided with a single non-on-body calibrated exposimeter. This is in line with earlier studies (Bolte et al., 2011; Neubauer et al., 2010; Thielens et al., 2015a) that demonstrated that a non-on-body calibrated exposimeter would underestimate personal exposure to incident RF EMFs due to the shielding of the body. Previous controlled measurements or modelling studies (Blas et al., 2007; Iskra et al., 2010; Neubauer et al., 2010) also found an underestimation of RF-EMF exposures due to body shielding, which is comparable to that estimated in our study. Future research should investigate this further in order to better explain the magnitude of effect that body shielding may have in underestimating microenvironmental personal RF-EMF exposure measurements.

Mobile phone frequency bands of 2600 MHz, WiMax 3.5 GHz, and ISM 5.8 GHz provided very little exposure. In Melbourne, 2600 MHz has recently been allocated to be used by mobile network providers; however, signals are mostly limited to some urban areas. The band has been officially sold for use in Belgium, but operation has not yet started (SpectrumMonitoring, 2016b). ISM 2.4 GHz shared a small portion of total exposures in both countries (see Table 2), and overall, there was no significant difference between indoor and outdoor microenviromental Wi-Fi 2.4 exposures in either country (results not shown).

Three or four microenvironments in the two countries shared the highest total exposures: the city center, urban parks, and outdoor residential areas. The fourth was a tram station in Belgium, which was located in the city center. The total exposure differences observed across the microenvironments in these two countries may be attributed to the differences in population density and physical infrastructure of Ghent and Melbourne. The exposure difference between the compared microenvironments in both countries was likely to be largely due to the contribution of total downlink exposure, which is generally higher for the microenvironments in Belgium.

The city center, train and airport in Australia (Melbourne) demonstrated higher exposures compared to the corresponding microenvironments in Belgium. Melbourne city center has higher population density and larger number of base stations providing higher capacity of telecommunication signals compared to the Ghent city center (OpenSignal, 2016; Antenna Site Register, 2016). The train travels in both countries involved journeys through the respective open areas of Melbourne and Ghent. In case of the train travel in Melbourne, high mobile phone signals can occur within the urban region (OpenSignal, 2016), especially with many people on board. Contrary to this, train travel from Ghent to Antwerp, a journey mostly through suburban and rural regions, the strength of RF-EMF signals, particularly of mobile phone base stations was weaker (Antenna Site Register, 2016). The total downlink exposure in the train in Belgium was found to be lower than that in the train in Australia, whereas the total uplink exposure scenario was found to be the opposite. This may be due to a higher path loss between the user and the network, which increases the DL signal that can reach the user and simultaneously increases the UL signal that is necessary to connect to the network. Furthermore, the train in Belgium had windows with metallic coating (Bhatt et al., 2016a), which provided highly attenuated DL signals and the mobile phone has to transmit at a higher power level to get past the metallic coating. Car travel in Australia was done in a less dense urban and suburban area of Melbourne, unlike in Belgium where it was mostly in highly dense urban areas. The resultant lower exposures in Australia for urban car travel were most likely due to this lower urban density.

The total exposure levels, including total DL and total uplink exposures, measured in our study are higher than those reported for similar European microenvironments, including Ghent (Bolte and Eikelboom, 2012; Joseph et al., 2010; Urbinello et al., 2014a, 2014b, 2014c). This could be because these studies did not correct for the consequence of body shielding on the measured personal exposure levels, which generally underestimates personal exposure levels (Bolte et al., 2011; Neubauer et al., 2010; Thielens et al., 2015a). However our study took this issue into account by using frequency-specific on-body calibration factors while estimating personal exposure levels. Furthermore, previous studies used different protocols (e.g. a single non-on-body calibrated exposimeter), measurement devices and analysis approaches compared to ours. Our study observed that personal exposures in urban microenvironments were much higher than those in rural and suburban microenvironments in Australia and Belgium. Furthermore, the exposure levels across indoor microenvironments were much lower than those across outdoor microenvironments. These findings are in line with the studies conducted in Europe (Bolte and Eikelboom, 2012; Joseph et al., 2010; Urbinello et al., 2014a, Vermeeren et al., 2013). In general, mobile phone base station exposure, the principal contributor to total RF-EMF exposure, is generally stronger in urban environments compared to rural and suburban environments (Antenna Site Register, 2016; OpenSignal, 2016; Radio Frequency National Site Archive, 2016). Amongst indoor stationary microenvironments, the library in Belgium and the airport in Australia provided the highest exposure levels. Interestingly, the library in Ghent was about 200 m from a nearby base station, which was exactly in line-of-sight. This also applied to the tram station in Ghent, which characterized the highest exposure level for outdoor microenvironments in Belgium.

The results demonstrated that total RF-EMF exposure levels varied for the majority of microenvironments in both countries. It is likely that relatively low dispersion of measurements (e.g. residential indoor and residential outdoor (rural/suburban) in Belgium) provide statistically significant differences in exposures, without having much differences in median exposures. While comparing these results, we therefore agree that exposure differences should not be solely interpreted on the basis of p-values (The American Statistical Association, 2016). Urbinello et al. (2014c) also showed that the environmental exposure levels of mobile phone DL signals varied across the same areas. Mobile phone DL signals, are the main contributor to the total exposure, and their subsequent variation, has a large effect in the total exposure. In general, diurnal variation in mobile phone signals in human environments is likely due to the variation of spatio-temporal factors (Manassas et al., 2012; Vermeeren et al., 2013; Urbinello et al., 2014c). Spatial factors, such as the location of the measurement sites (urban, suburban, rural, outdoor, indoor etc.), the proximity and number of nearby base stations; temporal factors (e.g. day, time and season when the measurements were performed), measurement path followed, and existing mobile phone traffic also affect the exposure levels (Bolte, 2016; Bolte and Eikelboom, 2012; Joseph and Verloock, 2010; Manassas et al., 2012; Roderíguez et al., 2011; Urbinello et al., 2014b; Viel et al., 2009; Vermeeren et al., 2013). The exposure variability in various microenvironments needs to be further examined with longer measurement times, at more spots within each microenvironment, and taking a greater number of repeated measurements controlling for spatio-temporal factors.

All exposure levels measured in our study were well below the reference levels for the general public as provided by the guidelines of the International Commission on Non-Ionizing Radiation Protection (ICNIRP, 1998) and the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) (Radiation Protection Standard, 2002). However, these guidelines are fundamentally designed to protect against acute (very short-term) RF-EMF health effects, particularly tissue heating. Biological effects have been shown at or below some levels we measured, including decrease in reproductive capacity, apoptotic cell death, and stress responses (Panagopoulos et al., 2010; Augner et al., 2010).

Since most of the exposure data measured in our study did not follow lognormal distributions, we were not able to apply a similar approach to deal with the censored data as used in previous studies (Bolte and Eikelboom, 2012; Frei et al., 2009; Joseph et al., 2010; Juhász et al., 2011; Urbinello et al., 2014a, 2014b). These studies used robust regression on order statistics (ROS) to treat the censored data in order to calculate summary statistics. In addition to ROS, there are other approaches to deal with censored data (i.e. non-detected): substitution, maximum likelihood estimation (MLE) methods, and Kaplan–Meier methods (Ganser and Hewett, 2010). However, the three most commonly used methods are substitution by LOD, LOD/2 and LOD/$\sqrt{2}$ (Hewett, 2007, Hewett and Ganser, 2007). The performance of these methods has been evaluated using simulations on single and contaminated lognormal data and it was found that LOD/$\sqrt{2}$ substitution method provided slightly positively biased means and negatively biased 95th percentiles, yet plausible results compared to more advanced approaches (Hewett and Ganser, 2007). Substitution methods have been used in RF-EMF personal exposure assessment elsewhere (Ibrani et al., 2016; Thomas et al., 2008; Röösli et al., 2008).

The evaluation of ROS and substitution (i.e. LOD) methods for RF-EMF exposure generally provided higher values of frequency band-specific summary statistics of exposures (i.e. means, medians, 25th, 75th and 95th percentiles) compared to the former method (Röösli et al., 2008). Röösli et al. (2008) also observed that the larger the proportion of censored data, the larger was the difference between the substitution (by LOD) and the ROS mean. The frequency-specific LODs for the exposimeter used in our study were lower compared to those employed in previous studies (EME SPY) (Bhatt et al., 2016b), which suggest that our devices were more sensitive than EME SPY.

### 4.2. Calibration of the exposimeters

As shown in Table 1, a majority (12 of 15) of the responses $R$ were lower than 1, which indicated that the ExpoM-RF underestimated personal exposure in these frequency bands without compensation. The responses in the 2600 MHz and the ISM 2.4 band were close to one. In the ISM 5.8 band, we found an overestimation of exposure by uncorrected measurements. The same underestimation was demonstrated previously (Bolte et al., 2011), where all but one frequency band showed a response $< 1$; and Thielens et al. (2015a) showed that all but two frequency bands showed a median response $< 1$.

The $PI_{50}$ values measured for the ExpoM-RF 64 ranged from 6.3 to 10 dB and no clear frequency dependence was observed. Thielens et al. (2015a) showed that the $PI_{50}$ values measured for individual exposimeters worn on the hip ranged from approximately 7 to 13 dB. Bolte et al. (2011) demonstrated these values to be up to approximately 20 dB. The $PI_{50}$ values are reduced in all frequency bands when an average over two ExpoM-RFs is considered, which is in agreement with previous findings (Thielens et al., 2015a; Bolte et al., 2011). The main reason for this reduction in $PI_{50}$ is the mirrored RF-EMF pattern of both ExpoM-RFs with regard to the sagittal plane of the subject. For certain azimuthal angles of incidence of RF-EMFs, one ExpoM-RF experiences a reduction in received power due to shadowing of the body, while the other ExpoM-RF experiences less or no shadowing at the same time. This consequently results in a more isotropic, average RF-EMF pattern and provides less variation in the distribution of the geometric averaged response.

The high cross-talk shown by the ISM 5.8 band was expected since this frequency band was the highest one, and had the highest potential to register harmonics from lower frequency bands. Similarly, DVB-T induced most cross-talk in other frequency bands, since it was the lowest frequency band. The cross-talk measured DVB-T was closer to a diagonal matrix than the one reported by Thielens et al. (2015a) using another type of exposimeter (EME SPY), where more off-diagonal elements were observed. Though the cross-talk observed in this study was determined using only the central frequencies of the bands, in reality the signals can also be emitted at the edges of the frequency bands and could thus induce a higher cross talk. Therefore, we also calibrated the ExpoM-RF 64 in a free space, using not only the central frequency, but also the two edges of the frequency bands.

The differences in the diagonal elements (shown in Tables B1 and B2, Appendix B) were higher than those obtained on the body for the lowest 10 frequency bands and higher than those presented in Table B1 for the five highest frequency bands. This was expected since there was no attenuating body next to the ExpoM-RF in free space. The off-diagonal elements were relatively low in a majority of the cases. Relatively high off-diagonal cross-talk values were measured between 800 DL and DVB-T and between 1800 DL and DECT bands. These values would be expected, since there is a relatively small difference of 1 MHz (800 DL and DVB-T) and

< 1 MHz (DECT and 1800 DL) between the edges of the considered frequency bands, respectively, in comparison to the bandwidth of the considered frequency bands. The highest off-diagonal cross-talk values in these frequency bands were also observed for either the lowest or highest frequency in the studied bands, which indicates that signals can also be emitted close to the edge of a band in reality, the on-body cross-talk values presented in Table B1 (Appendix B) might be higher as well. Relatively high off-diagonal cross-talk values were also found in the ISM 5.8 band in Table B1, Appendix B. We also observed cross-talk in the on-body matrix in Table B1 (Appendix B) in the same frequency band, but with a lower magnitude.

### 4.3. Strengths, limitations and implications

This is the first microenvironmental exposure study to assess far-field RF-EMF exposures from multiple sources across different microenvironments using a pair of *on-body* calibrated exposimeters. Consequently, our measurements have taken into account body shielding by using frequency-band specific calibration factors or the averaged response of two exposimeters. This means the exposures levels reported in this study provide reduced measurement uncertainties related to body shielding and are corrected for the underestimation caused by the absorption of RF-EMF by the human body. Our study is also the first micro-environmental RF-EMF exposure study which evaluated the performance of the exposimeters by using cross-talk measurements, which can be used to interpret the data collected. Furthermore, we evaluated exposure in the 2.6 GHz, WiMaX 3.5 GHz, and ISM 5.8 GHz bands, which were not included in previous studies. Only one recent study (Ibrani et al., 2016), has included evaluation of personal exposures from WiMax 3.5 GHz and ISM 5.8 bands. The exposimeters used in our study are more sensitive than other available and commonly used exposimeters (Bhatt et al., 2016b). The results of this study also allow us to make a valid comparison of the exposure levels across microenvironments in Australia and Belgium, which are characterized by different infrastructure, geo-physical, environmental and weather conditions. Therefore, the issue of measurements below the LODs is much less critical, which has been a major challenge in previous exposure assessments (Bolte and Eikelboom, 2012; Frei et al., 2009; Gajsek et al., 2013; Joseph et al., 2010; Juhász et al., 2011; Thomas et al., 2008; Urbinello et al., 2014b).

However, the study has the following limitations: i) we only involved one site/route per microenvironment and therefore our findings could only provide an estimate for microenvironmental exposure characterization, ii) not all measurements were repeated, iii) each measurement duration was only 15 min, iv) assessment of exposure variability involved only two measurements (15 min each), and v) many other sources of RF-EMF exposure in both countries (Australian Radiofrequency Spectrum Plan, 2013; Belgian Institute for Postal Services and Telecommunications, 2016; SpectrumMonitoring, 2016a, 2016b) could not be assessed due to the limitation of the measurement device. For instance, AM radio, which is a major source of environmental RF-EMF exposure in Melbourne (Henderson et al., 2014).

We have successfully performed personal far-field RF-EMF exposure assessment using on-body calibrated exposimeters. Therefore the approach contributes towards the development of improved exposure assessment methodology for epidemiological studies. Nevertheless, the application of multiple on-body calibrated exposimeters in epidemiological research may not always be the most rational approach. This is primarily because an on-body calibration is a resource intensive procedure, which is not achievable for large numbers of participants in epidemiological studies. In addition, it is not yet well understood how the results from a limited number of on-body calibrations for a small set of subjects can be translated into a general calibration factor useful for the whole population characterized with different body types (Bhatt et al., 2016a). However, it may still be useful to evaluate calibration factors for various body types, which could potentially be applied in exposure assessment for general populations.

## 5. Conclusions

We measured personal far-field RF-EMF exposure, frequency range 88 MHz to 5.8 GHz, in Australia and Belgium across various microenvironments using *on-body* calibrated exposimeters. Therefore, our study demonstrated that it was feasible to employ two exposimeters concurrently to estimate personal exposure minimizing the consequences of body shielding. Furthermore, our findings showed that the concurrent use of two on-body calibrated exposimeters provided the average exposure levels of 1.35 and 1.6 times higher in Australia and Belgium respectively, than those provided with a single non-on-body calibrated exposimeter. This implies that exposure assessment with the use of two on-body calibrated exposimeters has benefits over the use of a single non-on-body calibrated exposimeter and hence is recommended, if possible. Mobile phone base downlink exposures contributed the largest share to total exposures. Of 17 microenvironments compared, nine of them provided lower exposure levels in Melbourne (Australia) than the corresponding microenvironments in Ghent (Belgium). The personal exposures across urban microenvironments were lower than those in rural and suburban microenvironments. Similarly, exposure levels found across indoor microenvironments were lower than outdoors. Further studies are needed to provide more accurate exposure characterization considering multiple sites/routes per microenvironment.

## Appendix A

(See Table A1).

**Table A1**
Proportion of measured data (%) falling below the LODs of ExpoM-RFs across various microenvironments in Australia (n=19) and Belgium (n=19).

| Microenvironments | Countries | ExpoM-RF IDs | FM | DVT-T | 800 UL | 800 DL | 900 UL | 900 DL | 1800 UL | 1800 DL | DECT | 1900 UL | 2100 DL | ISM 2.4 | 2600 UL | 2600 DL | WiMax 3.5 | ISM 5.8 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Residential outdoor (urban) | Australia | 40 | 73, 76 | 0, 0 | 75, 78 | 40, 49 | 0, 0 | 0, 0 | 68, 91 | 0, 0 | 0, 0 | 96, 99 | 0, 0 | 9, 19 | 99, 100 | 16, 7 | 99, 99 | 53, 81 |
| | | 64 | 58, 68 | 4, 0 | 10, 37 | 31, 36 | 0, 0 | 0, 0 | 68, 89 | 0, 0 | 0, 0 | 96, 99 | 0, 0 | 0, 0 | 100, 100 | 16, 9 | 93, 97 | 63, 89 |
| | Belgium | 40 | 7, 0 | 0, 0 | 16, 8 | 93, 99 | 95, 91 | 0, 0 | 41, 36 | 0, 0 | 0, 0 | 99, 98 | 0, 0 | 0, 0 | 100, 100 | 100, 100 | 100, 98 | 54, 50 |
| | | 64 | 3, 0 | 3, 0 | 0, 0 | 97, 96 | 91, 83 | 0, 0 | 95, 76 | 0, 0 | 6, 0 | 99, 98 | 0, 0 | 0, 0 | 100, 100 | 100, 100 | 100, 100 | 85, 8 |
| Residential indoor (urban) | Australia | 40 | 100, 100 | 99, 4 | 96, 97 | 99, 100 | 0, 0 | 0, 0 | 97, 99 | 0, 0 | 4, 7 | 99, 99 | 0, 0 | 9, 21 | 100, 100 | 0, 0 | 100, 100 | 100, 100 |
| | | 64 | 100, 100 | 84, 40 | 72, 15 | 97, 99 | 0, 0 | 0, 0 | 97, 99 | 0, 0 | 19, 11 | 99, 99 | 0, 0 | 0, 0 | 100, 100 | 0, 0 | 100, 100 | 100, 100 |
| | Belgium | 40 | 14, 3 | 3, 0 | 20, 8 | 100, 32 | 96, 98 | 0, 0 | 94, 98 | 0, 0 | 24, 9 | 100, 100 | 0, 0 | 0, 0 | 100, 98 | 100, 100 | 100, 100 | 100, 100 |
| | | 64 | 17, 1 | 23, 12 | 0, 0 | 100, 8 | 97, 98 | 0, 0 | 99, 98 | 0, 0 | 89, 18 | 100, 100 | 0, 0 | 0, 0 | 100, 100 | 100, 100 | 99, 100 | 99, 100 |
| Office indoor (urban) | Australia | 40 | 88, 98 | 38, 40 | 97, 100 | 83, 97 | 34, 45 | 0, 0 | 92, 69 | 2, 4 | 68, 48 | 33, 40 | 0, 0 | 7, 5 | 100, 100 | 87, 86 | 100, 100 | 100, 100 |
| | | 64 | 99, 100 | 44, 44 | 80, 70 | 58, 46 | 7, 41 | 0, 0 | 95, 79 | 3, 13 | 80, 48 | 32, 45 | 0, 1 | 0, 0 | 100, 100 | 68, 48 | 100, 100 | 100, 100 |
| | Belgium | 40 | 94, 83 | 79, 64 | 18, 51 | 82, 66 | 58, 77 | 0, 0 | 76, 64 | 15, 26 | 23, 31 | 74, 66 | 6, 16 | 4, 8 | 85, 100 | 97, 100 | 100, 100 | 44, 71 |
| | | 64 | 85, 86 | 100, 99 | 3, 3 | 81, 59 | 52, 76 | 0, 0 | 80, 70 | 18, 20 | 25, 29 | 74, 64 | 8, 16 | 0, 0 | 78, 100 | 96, 100 | 97, 100 | 68, 83 |
| Park (urban) | Australia | 40 | 82, 96 | 0, 0 | 55, 41 | 5, 0 | 0, 0 | 0, 0 | 92, 93 | 0, 0 | 0, 0 | 100, 99 | 0, 0 | 34, 19 | 100, 100 | 1, 1 | 99, 97 | 75, 62 |
| | | 64 | 67, 90 | 0, 0 | 0, 10 | 0, 0 | 0, 0 | 0, 0 | 94, 96 | 0, 0 | 0, 0 | 99, 99 | 0, 0 | 0, 0 | 100, 100 | 0, 0 | 98, 95 | 94, 92 |
| | Belgium | 40 | 0, 0 | 0, 0 | 0, 0 | 99, 96 | 92, 92 | 0, 0 | 87, 85 | 0, 0 | 0, 0 | 99, 98 | 0, 0 | 35, 13 | 100, 100 | 100, 100 | 54, 21 | 94, 81 |
| | | 64 | 1, 0 | 0, 0 | 0, 0 | 100, 98 | 90, 88 | 0, 0 | 93, 90 | 0, 0 | 6, 0 | 100, 99 | 0, 0 | 0, 0 | 100, 100 | 100, 100 | 34, 13 | 98, 93 |
| City center | Australia | 40 | 0, 0 | 0, 0 | 25, 47 | 0, 0 | 0, 0 | 0, 0 | 0, 0 | 0, 0 | 0, 0 | 30, 39 | 0, 0 | 0, 0 | 29, 71 | 0, 0 | 5, 17 | 0, 0 |
| | | 64 | 0, 0 | 0, 0 | 0, 0 | 0, 0 | 0, 0 | 0, 0 | 0, 0 | 0, 0 | 0, 0 | 85, 84 | 0, 0 | 0, 0 | 1, 6 | 0, 0 | 2, 10 | 0, 0 |
| | Belgium | 40 | 0, 0 | 0, 0 | 0, 0 | 66, 90 | 57, 53 | 0, 0 | 17, 33 | 0, 0 | 0, 4 | 97, 92 | 0, 0 | 0, 1 | 100, 100 | 100, 100 | 89, 70 | 53, 89 |
| | | 64 | 0, 0 | 0, 0 | 0, 0 | 67, 87 | 38, 33 | 0, 0 | 16, 40 | 0, 0 | 0, 3 | 97, 88 | 0, 0 | 0, 0 | 100, 100 | 100, 100 | 74, 38 | 64, 95 |
| Library (urban) | Australia | 40 | 98, 94 | 14, 13 | 100, 100 | 99, 99 | 1, 3 | 0, 0 | 92, 81 | 2, 0 | 13, 14 | 80, 77 | 0, 1 | 1, 7 | 100, 100 | 100, 100 | 100, 100 | 98, 94 |
| | | 64 | 99, 96 | 88, 76 | 100, 100 | 69, 80 | 0, 0 | 0, 0 | 94, 91 | 4, 0 | 26, 42 | 80, 81 | 0, 0 | 0, 0 | 100, 100 | 100, 100 | 100, 100 | 99, 97 |
| | [a]Belgium | 40 | 0 | 0 | 0 | 99 | 96 | 0 | 84 | 0 | 0 | 97 | 0 | 0 | 100 | 100 | 2 | 67 |
| | | 64 | 0 | 0 | 0 | 99 | 90 | 0 | 91 | 0 | 0 | 100 | 0 | 0 | 100 | 100 | 1 | 35 |
| Shopping center (urban) | Australia | 40 | 99, 98 | 73, 52 | 99, 99 | 60, 55 | 71, 35 | 0, 0 | 69, 27 | 66, 66 | 85, 90 | 68, 61 | 31, 43 | 0, 5 | 99, 100 | 79, 84 | 100, 100 | 100, 100 |
| | | 64 | 99, 96 | 73, 60 | 98, 83 | 56, 40 | 64, 18 | 0, 0 | 71, 50 | 65, 65 | 82, 91 | 66, 60 | 32, 41 | 0, 0 | 98, 99 | 55, 59 | 100, 100 | 100, 100 |
| | [a]Belgium | 40 | 5 | 12 | 44 | 59 | 8 | 0 | 26 | 5 | 6 | 10 | 3 | 0 | 100 | 100 | 97 | 99 |
| | | 64 | 11 | 54 | 5 | 44 | 5 | 0 | 33 | 7 | 8 | 6 | 4 | 0 | 100 | 100 | 97 | 100 |
| Train station (urban) | Australia | 40 | 85, 99 | 0, 0 | 100, 100 | 0, 10 | 0, 0 | 0, 0 | 8, 24 | 0, 0 | 0, 0 | 52, 56 | 0, 0 | 0, 0 | 94, 96 | 3, 0 | 100, 100 | 14, 29 |
| | | 64 | 91, 91 | 0, 0 | 93, 91 | 0, 0 | 0, 0 | 0, 0 | 49, 43 | 0, 0 | 0, 0 | 48, 50 | 0, 0 | 0, 0 | 89, 99 | 0, 1 | 100, 100 | 48, 66 |
| | [a]Belgium | 40 | 1 | 1 | 56 | 77 | 13 | 0 | 31 | 1 | 17 | 46 | 0 | 9 | 98 | 100 | 81 | 77 |
| | | 64 | 3 | 4 | 13 | 51 | 9 | 0 | 38 | 8 | 22 | 50 | 0 | 0 | 100 | 100 | 55 | 81 |
| Tram station (urban) | Australia | 40 | 84, 59 | 0, 0 | 31, 38 | 3, 2 | 0, 0 | 0, 0 | 71, 72 | 0, 0 | 0, 0 | 86, 90 | 0, 0 | 2, 1 | 100, 99 | 0, 0 | 100, 100 | 99, 100 |
| | | 64 | 79, 48 | 0, 0 | 0, 0 | 0, 0 | 0, 0 | 0, 0 | 82, 80 | 0, 0 | 0, 0 | 90, 86 | 0, 0 | 0, 0 | 98, 96 | 0, 0 | 100, 100 | 100, 100 |
| | [a]Belgium | 40 | 0 | 0 | 0 | 100 | 77 | 0 | 64 | 0 | 0 | 100 | 0 | 97 | 100 | 100 | 0 | 7 |
| | | 64 | 0 | 0 | 0 | 77 | 36 | 0 | 34 | 0 | 0 | 99 | 0 | 96 | 98 | 100 | 0 | 9 |
| Bicycle (urban) | Australia | 40 | 14, 27 | 0, 0 | 50, 32 | 4, 3 | 0, 0 | 0, 0 | 64, 65 | 0, 0 | 2, 1 | 86, 89 | 0, 0 | 9, 11 | 92, 97 | 3, 1 | 95, 93 | 67, 66 |
| | | 64 | 15, 4 | 1, 8 | 21, 14 | 0, 1 | 0, 0 | 0, 0 | 75, 71 | 0, 0 | 4, 3 | 86, 90 | 0, 0 | 0, 0 | 93, 94 | 1, 0 | 97, 95 | 79, 76 |
| | [a]Belgium | 40 | 1 | 0 | 1 | 99 | 96 | 0 | 88 | 0 | 0 | 99 | 0 | 36 | 100 | 100 | 59 | 98 |
| | | 64 | 0 | 1 | 0 | 95 | 85 | 0 | 85 | 0 | 0 | 96 | 0 | 0 | 100 | 100 | 30 | 94 |
| Bicycle (rural/suburban) | [a]Belgium | 40 | 95 | 78 | 97 | 18 | 97 | 0 | 100 | 55 | 93 | 100 | 2 | 88 | 100 | 100 | 100 | 100 |
| | | 64 | 88 | 92 | 95 | 0 | 98 | 0 | 100 | 60 | 97 | 100 | 5 | 4 | 100 | 100 | 100 | 100 |
| Bus (urban) | Australia | 40 | 100, 54 | 7, 0 | 72, 88 | 54, 36 | 0, 0 | 0, 0 | 77, 97 | 0, 0 | 56, 24 | 21, 67 | 0, 0 | 34, 33 | 100, 100 | 100, 95 | 100, 100 | 84, 95 |
| | | 64 | 99, 68 | 30, 0 | 56, 71 | 33, 12 | 0, 0 | 0, 0 | 95, 98 | 0, 0 | 60, 26 | 7, 66 | 1, 0 | 0, 0 | 100, 100 | 100, 91 | 99, 100 | 92, 98 |
| | Belgium | 40 | 0, 3 | 0, 14 | 6, 31 | 86, 100 | 77, 92 | 0, 0 | 70, 74 | 0, 16 | 4, 41 | 88, 3 | 0, 0 | 0, 66 | 100, 100 | 100, 100 | 70, 90 | 95, 100 |
| | | 64 | 0, 13 | 0, 29 | 0, 4 | 84, 99 | 75, 92 | 0, 0 | 78, 75 | 0, 21 | 10, 49 | 87, 12 | 1, 0 | 0, 0 | 100, 100 | 100, 100 | 62, 89 | 98, 100 |
| Car (urban/suburban) | Australia | 40 | 72, 87 | 72, 75 | 100, 99 | 98, 98 | 74, 42 | 0, 0 | 99, 99 | 39, 33 | 85, 63 | 99, 100 | 28, 48 | 98, 99 | 100, 100 | 100, 100 | 100, 100 | 100, 100 |
| | | 64 | 63, 87 | 91, 90 | 91, 83 | 94, 96 | 62, 25 | 0, 0 | 99, 99 | 48, 31 | 84, 65 | 99, 99 | 31, 50 | 0, 0 | 100, 100 | 100, 100 | 100, 100 | 100, 100 |

**Table A1** (*continued*)

| Microenvironments | Countries | ExpoM-RF IDs | FM | DVT-T | 800 UL | 800 DL | 900 UL | 900 DL | 1800 UL | 1800 DL | DECT | 1900 UL | 2100 DL | ISM 2.4 | 2600 UL | 2600 DL | WiMax 3.5 | ISM 5.8 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Belgium | 40 | 3, 20 | 1, 0 | 18, 13 | 100, 99 | 92, 89 | 0, 0 | 86, 65 | 3, 0 | 11, 0 | 96, 100 | 0, 0 | 38, 38 | 100, 100 | 100, 100 | 71, 100 | 98, 91 |
| | | 64 | 41, 19 | 3, 34 | 2, 0 | 97, 100 | 90, 91 | 0, 0 | 91, 69 | 4, 0 | 14, 1 | 97, 100 | 1, 0 | 0, 0 | 100, 100 | 100, 100 | 60, 99 | 99, 100 |
| Car (rural/suburban) | [a]Belgium | 40 | 100 | 63 | 99 | 52 | 97 | 0 | 100 | 60 | 65 | 100 | 32 | 32 | 84 | 100 | 100 | 100 |
| | | 64 | 100 | 73 | 99 | 34 | 98 | 0 | 99 | 60 | 66 | 99 | 35 | 0 | 65 | 100 | 100 | 100 |
| Tram (urban) | Australia | 40 | 17, 25 | 0, 0 | 59, 52 | 44, 38 | 0, 0 | 0, 0 | 45, 14 | 0, 0 | 19, 22 | 49, 29 | 0, 0 | 2, 10 | 81, 85 | 0, 0 | 98, 99 | 81, 75 |
| | | 64 | 13, 10 | 0, 0 | 17, 8 | 12, 0 | 0, 0 | 0, 0 | 54, 17 | 0, 0 | 22, 36 | 46, 26 | 0, 0 | 0, 0 | 73, 84 | 0, 0 | 98, 98 | 86, 84 |
| | [a]Belgium | 40 | 0 | 0 | 23 | 53 | 71 | 0 | 66 | 0 | 2 | 62 | 0 | 2 | 100 | 100 | 70 | 96 |
| | | 64 | 0 | 0 | 0 | 40 | 68 | 0 | 73 | 0 | 2 | 69 | 0 | 0 | 100 | 100 | 96 | 97 |
| Train | Australia | 40 | 99, 100 | 12, 5 | 78, 80 | 46, 27 | 0, 0 | 0, 0 | 0, 19 | 14, 7 | 32, 26 | 1, 10 | 18, 3 | 0, 18 | 88, 98 | 78, 8 | 99, 100 | 70, 89 |
| | | 64 | 99, 100 | 28, 22 | 21, 34 | 1, 12 | 0, 0 | 0, 0 | 3, 24 | 8, 7 | 27, 31 | 2, 10 | 16, 5 | 0, 0 | 74, 91 | 70, 73 | 99, 99 | 85, 97 |
| | Belgium | 40 | 78, 81 | 47, 73 | 53, 59 | 71, 60 | 70, 2 | 0, 0 | 94, 66 | 42, 51 | 58, 71 | 57, 3 | 22, 9 | 94, 43 | 100, 100 | 100, 100 | 96, 97 | 100, 84 |
| | | 64 | 59, 83 | 56, 77 | 7, 10 | 68, 50 | 68, 1 | 0, 0 | 94, 62 | 41, 47 | 62, 77 | 59, 3 | 20, 14 | 0, 0 | 100, 92 | 100, 100 | 93, 94 | 100, 91 |
| [a]Subway station/ride (urban) | Australia | 40 | 24 | 95 | 98 | 63 | 2 | 0 | 94 | 12 | 8 | 58 | 96 | 47 | 100 | 100 | 100 | 97 |
| | | 64 | 5 | 84 | 59 | 85 | 0 | 0 | 94 | 8 | 7 | 58 | 95 | 0 | 98 | 100 | 100 | 97 |
| Residential outdoor (rural/ suburban) | Australia | 40 | 28, 4 | 11, 6 | 100, 100 | 99, 100 | 11, 4 | 0, 0 | 100, 100 | 11, 1 | 56, 23 | 100, 99 | 0, 0 | 97, 81 | 100, 100 | 100, 100 | 100, 100 | 100, 100 |
| | | 64 | 3, 15 | 46, 53 | 96, 100 | 89, 98 | 1, 0 | 0, 0 | 100, 100 | 11, 4 | 77, 34 | 100, 100 | 0, 1 | 0, 0 | 100, 100 | 100, 100 | 100, 100 | 100, 100 |
| | Belgium | 40 | 100, 100 | 100, 58 | 31, 16 | 99, 100 | 96, 99 | 0, 0 | 98, 100 | 43, 50 | 98, 98 | 100, 99 | 25, 16 | 42, 74 | 100, 100 | 98, 100 | 99, 100 | 99, 100 |
| | | 64 | 99, 100 | 100, 99 | 0, 0 | 98, 100 | 98, 98 | 0, 0 | 98, 100 | 53, 55 | 99, 100 | 99, 100 | 34, 20 | 13, 0 | 99, 100 | 100, 100 | 99, 100 | 100, 100 |
| Residential indoor (rural/ suburban) | [a]Australia | 40 | 4 | 99 | 100 | 99 | 98 | 0 | 100 | 2 | 76 | 100 | 41 | 91 | 100 | 100 | 100 | 100 |
| | | 64 | 15 | 100 | 99 | 100 | 72 | 0 | 100 | 7 | 100 | 100 | 63 | 0 | 100 | 100 | 100 | 100 |
| | Belgium | 40 | 100, 100 | 100, 99 | 100, 100 | 99, 100 | 92, 100 | 0, 0 | 100, 100 | 99, 100 | 99, 100 | 99, 100 | 100, 99 | 0, 0 | 100, 99 | 100, 100 | 100, 100 | 100, 100 |
| | | 64 | 100, 100 | 100, 99 | 89, 59 | 99, 100 | 91, 99 | 4, 0 | 100, 100 | 99, 100 | 100, 99 | 99, 100 | 99, 100 | 0, 0 | 99, 100 | 100, 100 | 100, 100 | 100, 100 |
| [a]Airport indoor | Australia | 40 | 100 | 65 | 95 | 85 | 7 | 0 | 53 | 5 | 62 | 16 | 0 | 0 | 100 | 48 | 100 | 73 |
| | | 64 | 100 | 67 | 78 | 67 | 4 | 0 | 54 | 2 | 61 | 16 | 0 | 0 | 95 | 41 | 100 | 89 |
| | Belgium | 40 | 100 | 94 | 100 | 100 | 22 | 0 | 1 | 0 | 23 | 9 | 0 | 0 | 100 | 100 | 100 | 83 |
| | | 64 | 100 | 92 | 100 | 100 | 18 | 0 | 6 | 0 | 48 | 17 | 0 | 0 | 100 | 100 | 100 | 95 |
| [a]Mountain/forest (rural) | Australia | 40 | 100 | 91 | 100 | 100 | 100 | 0 | 100 | 100 | 100 | 100 | 100 | 100 | 99 | 100 | 100 | 100 |
| | | 64 | 100 | 100 | 99 | 100 | 100 | 0 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |

[a]Single measurement.

## Appendix B

*Calibration procedure*

The calibration procedure consisted of two steps. In step one, the $E_{inc}$ emitted by the transmitting antenna ($T_X$) was measured without the subject present. For this, measurements of $E_{inc}$ were carried out along a vertical axis on the future assigned position of the subject in the measurement set-up using a Narda NBM-550 broadband field meter (Narda, Hauppauge, NY, USA). The (quadratic) $E_{inc}$ values were then averaged over the height of the subject. This was repeated for two orthogonal polarizations of the $T_X$: parallel to the four walls of the chamber (V polarization) and parallel to the floor of the chamber (H polarization). This was also repeated for every center frequency of the 15 frequency bands (DVB-T and higher) that could be calibrated in the available chamber.

In step two, the subject equipped with the ExpoM-RF 64 took place on the rotational platform in the far field of the $T_X$ (see Fig. 1a). The subject was rotated over 360° in azimuthal direction, while being exposed to the previously measured constant incident $E_{inc}$, which was V-polarized during a first rotation and then H-polarized. This rotation is executed in order to emulate an unknown orientation of the subject in an exposure situation (Thielens et al., 2013). During these rotations the $T_X$ subsequently emitted each one of the central frequencies of the studied frequency bands, while the ExpoM-RF recorded the electric fields on the body ($E_{body}$). This resulted in 60 measurements of $E_{body}$ per rotation (one each 6°) for two polarizations and 15 frequency bands.

The recorded $E_{body}$ values were not the same as the incident fields (Thielens et al., 2015a), but rather provided a distribution depending on the angle of incidence and the incident polarization (Thielens et al., 2013, 2015b; Vanveerdeghem et al., 2015). Therefore, the ratio of $E_{body}$ and $E_{inc}$ was studied using the ExpoM-RF's response, $R = E_{body}/E_{inc}$, where $R > 1$ indicated an overestimation of $E_{inc}$, and $R < 1$ indicated an underestimation. $R$ was determined in the post-processing of the calibration measurements, where a uniformly random angle of incidence and polarization was considered to determine the distribution of $R$. This distribution is characterized by its median value ($p_{50}(R)$) and its 50% prediction interval ($PI_{50}$):

$$PI_{50} = \frac{p_{75}(R)}{p_{25}(R)} \tag{1}$$

with $p_{75}(R)$ and $p_{25}(R)$ indicating the 75th and 25th percentiles of $R$, respectively. A small value of $PI_{50}$ is desirable.

During the exposure assessment in the microenvironments, the ExpoM-RFs measured $E_{body}$ values, which were used to estimate incident field strengths ($\hat{E}_{inc}$), using this response. In this study, we estimated $\hat{E}_{inc}$, using the median ($p_{50}(R)$):

$$\hat{E}_{inc} = \frac{E_{meas}}{p_{50}(R)} \tag{2}$$

with $E_{meas}$, the measured electric field strength. The uncertainty on this estimation is quantified using the $PI_{50}$.

Thielens et al. (2015a, (2015b) demonstrated that the $PI_{50}$ value can be reduced, when multiple exposimeters are used simultaneously. Therefore, the subject was equipped with one ExpoM-RF on each hip, during the exposure assessment. Since only one ExpoM-RF was calibrated on the body, the same response was assumed for the second one, with this difference that the angular dependence was reflected with respect to the sagittal plane of the subject. The measured electric field values were averaged using a geometric average and were corrected for the influence of the body using Eq. (2).

During the calibration measurements, $E_{body}$ values were registered in each frequency band, regardless of the emitted frequency. These measurements were used to determine the cross-talk of the ExpoM-RF. Cross-talk is defined as the ratio of the electric field strength value registered in a certain frequency band and the incident field strength in the band in which the electric field was actually emitted. Ideally, the cross-talk matrix equals the identity matrix: one on the main diagonal and zero off-diagonal. However, Thielens et al. (2015a) demonstrated that exposimeters can exhibit large off-diagonal cross-talk values. Cross-talk is problematic for personal exposure measurements, since it causes the registration of non-existent exposure values.

Following the on-body calibration, the ExpoM-RF 64 was also calibrated in free-space in the same anechoic chamber. Firstly, the ExpoM-RF 64 was placed vertically at a height of 1.5 m above the rotating platform supported by a polystyrene arm, while the $T_X$ was oriented vertically as well. The $T_X$ subsequently emitted a continuous wave at the lowest frequency, the central frequency, and the highest frequency in each of the 15 studied frequency bands, with a constant input power in the antenna. Simultaneously, the ExpoM-RF recorded electric field values ($E_{expom}$). These were then divided by the $E_{inc}$ values measured in the previous on-body calibration in order to determine the free-space cross-talk and responses (see Table B2, Appendix B).

(See Tables B1 and B2).

**Table B1**
Median cross-talk values of ExpoM-RF 64 measured on the body of the subject.

| Received | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Emitted** | **DVB-T** | **800 UL** | **800 DL** | **900 UL** | **900 DL** | **1800 UL** | **1800 DL** | **DECT** | **1900 UL** | **2100 DL** | **ISM 2.4** | **2600 UL** | **2600 DL** | **WiMAX 3.5** | **ISM 5.8** |
| **DVB-T** | 0.48 | 0.05 | 0.04 | 0.05 | 0.08 | 0.02 | 0.02 | 0.02 | 0.01 | 0.02 | 0.07 | 0.02 | 0.02 | 0.02 | 0.03 |
| **800 UL** | 0.03 | 0.58 | 0.01 | 0.01 | 0.02 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.01 |
| **800 DL** | 0.00 | 0.02 | 0.47 | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.02 |
| **900 UL** | 0.00 | 0.01 | 0.01 | 0.53 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.01 |
| **900 DL** | 0.00 | 0.01 | 0.01 | 0.01 | 0.44 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.01 |
| **1800 UL** | 0.00 | 0.01 | 0.01 | 0.01 | 0.02 | 0.55 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.07 |
| **1800 DL** | 0.00 | 0.01 | 0.01 | 0.01 | 0.02 | 0.01 | 0.43 | 0.01 | 0.00 | 0.00 | 0.02 | 0.00 | 0.00 | 0.00 | 0.07 |
| **DECT** | 0.00 | 0.01 | 0.01 | 0.01 | 0.02 | 0.01 | 0.25 | 0.49 | 0.00 | 0.00 | 0.02 | 0.01 | 0.00 | 0.00 | 0.07 |
| **1900 UL** | 0.01 | 0.01 | 0.01 | 0.01 | 0.02 | 0.01 | 0.01 | 0.00 | 0.73 | 0.01 | 0.02 | 0.01 | 0.00 | 0.01 | 0.13 |
| **2100 DL** | 0.01 | 0.01 | 0.01 | 0.01 | 0.02 | 0.01 | 0.01 | 0.00 | 0.00 | 0.72 | 0.02 | 0.01 | 0.00 | 0.01 | 0.10 |
| **ISM 2.4** | 0.01 | 0.02 | 0.01 | 0.01 | 0.03 | 0.01 | 0.01 | 0.00 | 0.00 | 0.01 | 0.99 | 0.01 | 0.01 | 0.01 | 0.02 |
| **2600 UL** | 0.01 | 0.01 | 0.01 | 0.01 | 0.02 | 0.01 | 0.01 | 0.00 | 0.01 | 0.01 | 0.02 | 1.29 | 0.01 | 0.01 | 0.05 |
| **2600 DL** | 0.01 | 0.01 | 0.01 | 0.01 | 0.02 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.02 | 0.01 | 1.07 | 0.01 | 0.09 |
| **WiMAX 3.5** | 0.01 | 0.01 | 0.01 | 0.01 | 0.02 | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 | 0.01 | 0.89 | 0.35 |
| **ISM 5.8** | 0.01 | 0.02 | 0.02 | 0.02 | 0.04 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.03 | 0.01 | 0.01 | 0.01 | 3.13 |

**Table B2**
Median cross-talk values of ExpoM-RF 64 measured off-body for a vertically polarized $T_X$ antenna and a vertically placed ExpoM-RF 64 for the lower edge, the middle, and the upper edge of the listed frequency bands, respectively.

**Received**

| Emitted | DVB-T | 800 UL | 800 DL | 900 UL | 900 DL | 1800 UL | 1800 DL | DECT | 1900 UL | 2100 DL | ISM 2.4 | 2600 UL | 2600 DL | WiMAX 3.5 | ISM 5.8 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **DVB-T** | 2.12–2.6–1.38 | 0.06–0.05–6.05 | 0.05–0.04–0.05 | 0.04–0.04–0.04 | 0.09–0.09–0.09 | 0.03–0.03–0.03 | 0.02–0.02–0.02 | 0.02–0.02–0.02 | 0.02–0.02–0.02 | 0.02–0.02–0.02 | 0.08–0.07–0.07 | 0.02–0.02–0.02 | 0.02–0.02–0.02 | 0.02–0.02–0.02 | 0.04–0.05–0.05 |
| **800 UL** | 0.35–0.15–0.01 | 1.62–1.81–1.6 | 0.01–0.01–0.02 | 0.01–0.01–0.01 | 0.02–0.02–0.02 | 0.01–0.01–0.01 | 0.01–0.01–0.01 | 0–0–0 | 0–0–0 | 0–0–0 | 0.02–0.01–0.02 | 0.01–0.01–0.01 | 0–0–0 | 0.01–0.01–.01 | 0.02–0.01–0.01 |
| **800 DL** | 0.01–0.01–0.01 | 0.03–0.04–0.02 | 1.2–1.43–1.14 | 0.01–0.01–0.01 | 0.02–0.02–0.02 | 0.01–0.01–0.01 | 0.01–0.01–0.01 | 0–0–0 | 0–0–0 | 0–0–0 | 0.02–0.01–0.01 | 0–0–0 | 0–0–0 | 0–0–0 | 0.01–0.01–0.02 |
| **900 UL** | 0–0–0 | 0.02–0.01–0.01 | 0.01–0.01–0.01 | 1.03–1.29–0.59 | 0.02–0.02–0.02 | 0.01–0–0.01 | 0–0–0 | 0–0–0 | 0–0–0 | 0–0–0 | 0.01–0.01–0.02 | 0–0–0 | 0–0–0 | 0–0–0 | 0.01–0.01–0.01 |
| **900 DL** | 0–0–0 | 0.01–0.01–0.01 | 0.01–0.01–0.01 | 0.01–0.01–0.01 | 1.2–0.67–0.32 | 0.01–0.01–0.01 | 0–0–0 | 0–0–0 | 0–0–0 | 0–0–0 | 0.02–0.02–0.02 | 0–0–0 | 0–0–0 | 0–0–0 | 0.01–0.01–0.02 |
| **1800 UL** | 0–0–0 | 0.01–0.01–0.01 | 0.01–0.01–0.01 | 0.01–0.01–0.01 | 0.02–0.02–0.02 | 0.99–1.25–1.01 | 0–0–0.05 | 0–0–0 | 0–0–0 | 0–0–0 | 0.01–0.01–0.01 | 0–0–0 | 0–0–0 | 0–0–0 | 0.12–0.17–0.18 |
| **1800 DL** | 0.01–0.01–0.01 | 0.01–0.01–0.01 | 0.01–0.01–0.01 | 0.01–0.01–0.01 | 0.03–0.02–0.02 | 0.01–0.01–0.01 | 0.88–0.97–0.8 | 0–0.02–1.04 | 0–0–0 | 0–0–0.01 | 0.03–0.05–0.04 | 0–0.01–0.01 | 0–0–0 | 0–0–0 | 0.19–0.17–0.07 |
| **DECT** | 0.01–0.01–0.01 | 0.01–0.01–0.01 | 0.01–0.01–0.01 | 0.01–0.01–0.01 | 0.02–0.02–0.02 | 0.01–0.01–0.01 | 0.85–0.53–0.06 | 1.1–1.06–1 | 0–0.01–0.08 | 0.01–0.01–0.01 | 0.04–0.03–0.02 | 0.01–0.01–0.01 | 0–0–0 | 0–0–0 | 0.07–0.15–0.11 |
| **1900 UL** | 0.01–0.01–0.01 | 0.01–0.01–0.01 | 0.01–0.01–0.01 | 0.01–0.01–0.01 | 0.03–0.02–0.02 | 0.01–0.01–0.01 | 0.01–0.01–0.01 | 0.01–0–0 | 1.2–0.98–0.71 | 0.01–0.01–0.01 | 0.02–0.02–0.02 | 0.01–0.01–0.01 | 0–0–0 | 0.01–0.01–0.01 | 0.1–0.2–0.22 |
| **2100 DL** | 0.01–0.01–0.01 | 0.01–0.01–0.01 | 0.01–0.01–0.01 | 0.01–0.01–0.01 | 0.02–0.02–0.02 | 0.01–0.01–0.01 | 0.01–0.01–0.01 | 0–0–0 | 0–0–0 | 1.34–1.2–0.89 | 0.03–0.03–0.03 | 0.01–0.01–0.01 | 0–0–0 | 0.01–0.01–0.01 | 0.18–0.17–0.13 |
| **ISM 2.4** | 0.01–0.01–0.01 | 0.02–0.01–0.01 | 0.01–0.01–0.01 | 0.01–0.01–0.01 | 0.02–0.02–0.02 | 0.01–0.01–0.01 | 0.01–0.01–0.01 | 0–0–0 | 0–0–0 | 0.01–0.01–0.01 | 1.18–1.26–0.51 | 0.01–0.01–0.36 | 0.01–0.01–0.01 | 0.01–0.01–0.01 | 0.03–0.03–0.04 |
| **2600 UL** | 0.01–0.01–0.01 | 0.02–0.01–0.01 | 0.01–0.01–0.01 | 0.01–0.01–0.01 | 0.02–0.02–0.02 | 0.01–0.01–0.01 | 0.01–0.01–0.01 | 0–0–0 | 0–0–0 | 0.01–0.01–0.01 | 0.02–0.02–0.02 | 0.61–1.02–1.26 | 0.01–0.01–0.01 | 0.01–0.01–0.01 | 0.03–0.04–0.04 |
| **2600 DL** | 0.01–0.01–0.01 | 0.02–0.01–0.01 | 0.01–0.01–0.01 | 0.01–0.01–0.01 | 0.03–0.03–0.03 | 0.01–0.01–0.01 | 0.01–0.01–0.01 | 0.01–0.01–0.01 | 0.01–0.01–0.01 | 0.01–0.01–0.01 | 0.02–0.02–0.02 | 0.01–0.01–0.01 | 0.77–0.64–0.79 | 0.01–0.01–0.01 | 0.06–0.06–0.07 |
| **WiMAX 3.5** | 0.01–0.01–0.01 | 0.01–0.01–0.01 | 0.01–0.01–0.01 | 0.01–0.01–0.01 | 0.02–0.02–0.02 | 0.01–0.01–0.01 | 0.01–0.01–0.01 | 0–0–0 | 0–0–0 | 0–0–0 | 0.02–0.01–0.01 | 0.01–0.01–0.01 | 0.01–0.01–0.01 | 0.7–0.38–0.2 | 0.19–0.14–0.05 |
| **ISM 5.8** | 0.01–0.01–0.01 | 0.02–0.02–0.02 | 0.02–0.02–0.02 | 0.02–0.02–0.02 | 0.04–0.04–0.04 | 0.01–0.01–0.01 | 0.01–0.01–0.01 | 0.01–0.01–0.01 | 0.01–0.01–0.01 | 0.01–0.01–0.01 | 0.03–0.03–0.03 | 0.01–0.01–0.01 | 0.01–0.01–0.01 | 0.01–0.01–0.01 | 1.3–2.17–1.23 |

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