Environment International 156 (2021) 106711

Contents lists available at ScienceDirect

Environment International

journal homepage: www.elsevier.com/locate/envint

Exposure to radiofrequency electromagnetic fields: Comparison of exposimeters with a novel body-worn distributed meter

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ARTICLE INFO

Handling Editor: Olga-Ioanna Kalantzi

Keywords:
Measurements
RF-EMF
ExpoM-RF
EME SPY
Comparison exposimeters
Microenvironments
Body-Worn Distributed Meter

ABSTRACT

Background: Exposure to radiofrequency electromagnetic fields (RF-EMF) is often measured with personal exposimeters, but the accuracy of measurements can be hampered as carrying the devices on-body may result in body shielding. Further, the compact design may compromise the frequency selectivity of the sensor. The aim of this study was to compare measurements obtained using a multi-band body-worn distributed-exposimeter (BWDM) with two commercially available personal exposimeters (ExpoM-RF and EmeSpy 200) under real-life conditions.

Methods: The BWDM measured power density in 10 frequency bands (800, 900, 1800, 2100, 2600 MHz, DECT 1900 MHz, WiFi 2.4 GHz; with separate uplink/downlink bands for 900, 1800 and 2100 MHz); using 20 separate antennas integrated in a vest and placed on diametrically opposite locations on the body, to minimize body-shielding. RF-EMF exposure data were collected from several microenvironments (e.g. shopping areas, train stations, outdoor rural/ urban residential environments, etc.) by walking around pre-defined areas/routes in Belgium, Spain, France, the Netherlands and Switzerland. Measurements were taken every 1–4 s with the BWDM in parallel with an ExpoM-RF and an EmeSpy 200 exposimeter. We calculated medians and interquartile ranges (IQRs) and compared difference, ratios and correlations of geometric mean RF-EMF exposure levels per microenvironment as measured with the exposimeters and the BWDM.

Results: Across 267 microenvironments, medians and IQR of total BWDM measured RF-EMF exposure was 0.13 (0.05–0.33) mW/m^2. Difference: IQR of exposimeters minus BWDM exposure levels was −0.011 (−0.049 to 0.0095) mW/m^2 for the ExpoM-RF and −0.056 (−0.14 to −0.017) for the EmeSpy 200; ratios (exposimeter/ BWDM) of total exposure had an IQR of 0.79 (0.55–1.1) for the ExpoM-RF and 0.29 (0.22–0.38) for the EmeSpy 200. Spearman correlations were 0.93 for the ExpoM-RF vs the BWDM and 0.96 for the EmeSpy 200 vs the BWDM.

Discussion and conclusions: Results indicate that exposimeters worn on-body provide somewhat lower total RF-EMF exposure as compared to measurements conducted with the BWDM, in line with effects from body shielding. Ranking of exposure levels of microenvironments showed high correspondence between the different device types. Our results are informative for the interpretation of existing epidemiological research results.

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https://doi.org/10.1016/j.envint.2021.106711
Received 18 December 2020; Received in revised form 15 April 2021; Accepted 8 June 2021

1. Introduction

Telecommunication technology has proliferated over the past decades and nowadays virtually everybody is exposed to radiofrequency electromagnetic fields (RF-EMF). Epidemiological studies evaluating possible health risks associated with the exposure to RF-EMF depend on accurate assessment of the exposure. Several approaches have been applied in epidemiological studies, including questionnaires inquiring about use patterns of RF-EMF emitting devices (e.g. number and duration of mobile phone calls, duration of streaming video on laptops, etc. (Auvinen et al., 2019; Goedhart et al., 2018; Guxens et al., 2016), alone or in combination with modelling of ambient exposure from fixed-site transmitters (Varsier et al., 2015) or using mobile or personal measurements (Frei et al., 2010; Urbinello et al., 2014). Measurements are often regarded as gold standard to assess a person's RF-EMF exposure. However, they are time and work intensive and therefore costly. Nowadays, exposimeters exist that are small and light enough to be carried around and with enough memory space to log exposure continuously over a period of time. Such exposimeters include for example the EmeSpy types 120, 140 or 200 (Satimo/MVG, Villejuist, France), or the ExpoM-RF (further called "ExpoM"; Fields at Work, Zurich, Switzerland).

Shortcomings of these devices that have been previously mentioned include for example a) underestimation of exposure due to body shielding; b) that exposimeters are calibrated in free space but often used on-body in studies; and c) their inherent measurement uncertainty. In addition, it has been criticized that differences in wearing position or orientation of exposimeters may mean that the comparison of exposures across microenvironments may not be valid (Bolte, 2016; Thielens et al., 2013; Thielens et al., 2016). Variation in logging intervals have also been discussed to lead to underestimation of average exposures, with lower chances of capturing peak exposures with increasing logging intervals (e.g. logging every 90 s instead of every 3–4 s; (Bolte, 2016). A dedicated, on-body calibrated improved measurement device designed to avoid body shielding would be considered to be the gold standard. But it has not yet been evaluated under real-life conditions whether such measurements would actually provide different results than personal measurements with exposimeters.

To assess this question, we applied a body-worn distributed meter (BWDM, (Aminzadeh et al., 2018; Aminzadeh et al., 2019) that uses 20 sensors for 10 different frequency bands, distributed over the torso, integrated into a wearable vest and calibrated on body (i.e. calibrated while worn by respective research assistant in the lab). We have previously evaluated the BWDM under well-defined conditions in an anechoic chamber (Aminzadeh et al., 2018; Aminzadeh et al., 2019). However, such an approach generally disregards several factors: a) Exposure situations under real-life conditions are usually more complex and diffuse, stemming from a multitude of sources; b) laboratory conditions for calibration purposes are usually set to center-frequencies of frequency bands and with continuous wave instead of real signals, while in reality various frequencies within bands are used simultaneously, leading to more cross-talk; c) handling of devices may differ during a real-life measurement study compared to the situation in a lab. We therefore set out to compare two commercial exposimeters in addition to a BWDM under real-life outdoor and indoor conditions. Such comparisons are important for the interpretation of previous personal and microenvironmental exposure studies that relied on commercial exposimeters. Please note that an overview of the results of the measurement campaigns as such is provided elsewhere (Eeftens, in preparation).

The aims of our study were to 1) compare BWDM-measurements with results from simultaneously worn personal exposimeters, specifically the ExpoM and the EmeSpy 200 (further called "EmeSpy"), 2) to assess over- or underestimation of exposure across types of signals (total, downlink, uplink or digital enhanced cordless telecommunication (DECT) and wireless local area networking (WiFi) signals), and 3) to assess the effect of logging intervals on average exposures.

2. Methods

2.1. Measurement areas and sets

We used data collected in the framework of the project ACCEDERA: *Improving the accuracy of personal RF-EMF measurements and characterization of exposure levels in different environments across countries* (SwissTPH, 2020). We collected RF-EMF measurements in five European countries (Belgium, France, Spain, Switzerland and the Netherlands). Measurements were conducted in several cities (Paris and Amiens, Barcelona and Tarragona, Brussels and Ghent, Zurich and Basel, Utrecht and surrounding) and in different types of microenvironments, such as downtown shopping areas, decentral and central residential areas, playgrounds, parks, train stations, bus stops, university libraries and so on (supplemental Table ST1). The idea of including these different types of microenvironments was to collect average exposures in such "typical" environments that may display a broad range of exposure situations. The first measurements were collected in 2016 and the last in 2018. Researchers of each country defined a specific list of microenvironments to be measured and performed two sets of measurements. Each set lasted for about two months and included a repeat round of measurements using the identical measurement route and microenvironment. After the two months, the BWDM was handed over to the next country's measurement team. After all countries had performed the first set of measurements, the BWDM was returned to Ghent University for (on body) calibration, and subsequently the second set of measurements was started.

2.2. Measurement devices

Three different devices were deployed in parallel: A newly developed body-worn distributed meter (BWDM) (Aminzadeh et al., 2018; Aminzadeh et al., 2019) in addition to two commercially available exposimeters, namely the EmeSpy and the ExpoM. All included frequency bands in the current comparison are shown in Table 1, and all available frequency bands per device are shown in supplemental Table ST2. All comparisons shown here pertain to those bands that were available in all three devices.

The BWDM prototype was developed for simultaneous measurements of power density in 10 frequency bands (Long Term Evolution (LTE) 800 and 2600 MHz, 900 MHz, 1800 MHz, 2100 MHz, DECT, and WiFi 2.4 GHz; including uplink and downlink bands). The BWDM consists of 20 separate antennas integrated in a vest, distributed in an optimal way on the front and back of the human torso as well as right and left hips. For all frequency bands, antenna pairs were placed on diametrically opposite locations on the body, to minimize body-shielding (supplemental Figure SF1; (Aminzadeh et al., 2018). The BWDM was calibrated on-body under laboratory conditions for different body sizes and shapes (Aminzadeh et al., 2018). The ExpoM as well as the EmeSpy exposimeters have been described in more detail elsewhere (Bolte, 2016; Aminzadeh et al., 2019; Aminzadeh et al., 2016). In brief,

Table 1
Frequency bands included in current comparison (called "total" exposure).

	BWDM frequencies	ExpoM frequencies	EmeSpy frequencies
DL800	790–821 MHz	791–821 MHz	791–821 MHz
UL900	879–915 MHz	880–915 MHz	880–915 MHz
DL900	921–960 MHz	925–960 MHz	925–960 MHz
UL1800	1710–1785 MHz	1710–1785 MHz	1710–1785 MHz
DL1800	1805–1880 MHz	1805–1880 MHz	1805–1880 MHz
DECT	1880–1900 MHz	1880–1900 MHz	1880–1900 MHz
UL2100	1900–1980 MHz	1920–1980 MHz	1920–1980 MHz
DL2100	2110–2170 MHz	2110–2170 MHz	2110–2170 MHz
WIFI	2400–2485 MHz	2400–2485 MHz	2400–2483.5 MHz
DL2600	2620–2690 MHz	2620–2690 MHz	2620–2690 MHz

DL: Downlink, UL: Uplink

these are devices that measure narrowband exposure similar to the BWDM, but with some extra integrated bands, such as radio or TV (supplemental Table ST2).

During the first set of measurements, the EMESpy and the ExpoM were worn on the hips under the BWDM. During the calibration, after the first set of measurements had been finished in all countries, we observed that WiFi 5 GHz exposure in all countries was negligible and therefore it was considered that the sensors could be removed. Instead, the vest pouches were used for the two exposimeters for the second set of measurements. Because of the change in exposimeter placement, all results shown below pertain to the second measurement set only (for timing of the measurements see supplemental Table ST1).

2.3. *Data collection*

Trained field research assistants performed measurements in various indoor and outdoor microenvironments (supplemental Table ST1) in Belgium, Spain, France, Netherlands and Switzerland. Measurements were collected using the BWDM in parallel with an ExpoM and either an EmeSpy or a second ExpoM exposimeter, worn on opposite sides of the torso. Measurements were collected every 1–4 s depending on the measurement device, while walking pre-defined routes to capture different types of microenvironments. Each microenvironmental measurement was aimed to be measured for about 15 min and assistants were asked to switch off their mobile phones. All microenvironments were *a priori* defined, and timing and characteristics were recorded with an application on a mobile phone set to flight mode. The 15 min time interval was based on a previous assessment indicating a good balance between reproducible microenvironmental mean and feasibility of data collection (Röösli et al., 2015).

2.4. *Data cleaning and preparation*

Lower and upper limits of quantification (LoQ) in terms of power density varied per band for the EmeSpy and the ExpoM, and per single sensor and person for the BWDM, due to the person-specific calibration of the BWDM. These are provided in supplemental Tables ST3, ST4 and ST5. All measurements of all three devices were matched based on the time stamp. All exposures were expressed in mW/m^2.

In general, total or downlink signals did not fall below the lower LoQ. However, uplink, DECT as well as WiFi in some countries had a substantial proportion of measurements below the lower LoQ. For example, for the BWDM for DECT, the percentage of measurements below the LoQ was 32% and for WiFi it was 44%. In these cases, a value was provided by the device although it was outside of the calibrated range. Because it was assumed that these values would have a higher uncertainty but still contain quantitative information, original values were used in the calculations. The only exception was the DECT band, where crosstalk appeared to affect values below about 0.00067 mW/m^2. Therefore, for this band, individual measurement points below this value were judged to be unreliable and were set to be missing.

2.5. *Statistical analysis*

We calculated geometric means of RF-EMF exposure per route and microenvironment. Per device, we report here as “total exposure” only those frequencies with a complete overlap across the devices (Table 1). We compared devices using the total exposure of all 10 BWDM bands, in addition to all five downlink or three uplink frequency exposures, and DECT and 2 GHz WiFi exposure, with Spearman correlations. We were especially interested in exploring whether the ExpoM and EmeSpy would tend to overestimate or underestimate exposure as compared to measurements conducted with the BWDM. We assessed this by comparing absolute differences, ratios, and Spearman correlation coefficients of geometric means per microenvironment for the same bands as in the previous step (total, downlink, uplink, DECT, WiFi). All the aforementioned quantities were calculated using power densities in mW/m^2. Because of the higher proportion of measurement values below the LoQ for uplink, DECT and WiFi signals, we also recalculated Spearman correlation coefficients including all measurements that fell below the LoQ. We also produced Bland-Altman plots on log-transformed values (Bland and Altman, 1986).

Finally, we used the BWDM measurements that had been collected with a sampling interval of one measurement per second. We artificially generated larger sampling intervals between two and 90 s, as similar intervals have been previously applied in some epidemiological studies (Bolte et al., 2019; Frei et al., 2009). Equally spaced sampling intervals were generated, with random starting points within the first 1.5 min of the BWDM data files, and geometric mean (total) exposure of the whole data set was calculated for all generated sampling intervals. We then calculated and plotted ratios of the geometric means, so of the generated data sets containing a measurement every two to 90 s, vs the data set with one measurement per second interval. This was done to assess if indeed longer sampling intervals would lead to underestimating average exposures (Bolte, 2016).

3. Results

During the second set of measurements, we collected measurements of 267 microenvironments. Because many microenvironments were sampled twice, this corresponded to 488 geometric mean values. The number of measured microenvironments per participating country is given in supplemental Table ST1. The BWDM was used in 267 microenvironments, the ExpoM in 261 and the EmeSpy in 87. In 78 microenvironments, all three devices were used simultaneously. Unfortunately, due to different device failures, only measurements performed in Belgium and France contributed to those where all three devices worked simultaneously.

Overall, medians and interquartile ranges (IQR) of geometric means of total exposure across all microenvironments was 0.13 (0.05–0.33) mW/m^2 as measured with the BWDM (Table 2). Exposimeters compared to the BWDM tended to assess total exposure levels reasonably well: Fig. 1 shows a scatter plot of the geometric mean exposures per microenvironment assessed with exposimeters and plotted against measurements performed with the BWDM. Scatter plots (Fig. 2) as well as Bland-Altman plots (supplemental Figure SF2) indicated that differences between exposimeters were systematic and depended on the frequency band: BWDM measured clearly higher UL, DECT and WiFi exposure than the exposimeters. However, because DL contributed much more to the total exposure (average 73%), the underestimation within the other bands did not introduce major absolute errors when assessing total exposure (Fig. 3)

Across microenvironments, ratios (exposimeter power density values divided by BWDM) for total exposure were 0.79 (IQR 0.55–1.13) for the ExpoM, and 0.29 (0.22–0.38) for the EmeSpy, which means that exposure was estimated lower when using exposimeters as compared to measurements taken with the BWDM. Spearman correlations indicated exposimeters were well capable of ranking the average exposures per microenvironment: correlation coefficients of the ExpoM device and the BWDM over total microenvironmental exposure levels was 0.93. For the EmeSpy and the BWDM this value was 0.96. Again, for the separate bands, ratios and Spearman correlations differed but overall indicated mostly lower exposure for exposimeters (Table 2, Supplemental Table ST6).

Artificially extending the logging interval of the BWDM from 1 measurement per second to one measurement every 2–90 s produced some random error but no appreciable over- or underestimation of the exposure (Fig. 4, country-specific supplemental Figure SF3). Geometric mean ratios remained close to unity, within ratios of 0.97–1.03.

Table 2

Total, difference, ratios, Spearman correlation coefficients (rho).

		Total (mW/m^2), IQR	Difference(mW/m^2), IQR	Ratio, IQR	rho
Total	BWDM	0.13 (0.053;0.33)	–	–	1
	ExpoM	0.12 (0.033;0.28)	−0.011 (−0.049;0.0095)	0.79 (0.55;1.1)	0.93
	EmeSpy	0.03 (0.0084;0.073)	−0.056 (−0.14;−0.017)	0.29 (0.22;0.38)	0.96
DL	BWDM	0.082 (0.031;0.25)	–	–	1
	ExpoM	0.094 (0.027;0.25)	0.0021 (−0.012;0.049)	1.1 (0.69;1.6)	0.94
	EmeSpy	0.025 (0.0048;0.067)	−0.028 (−0.083;−0.0052)	0.32 (0.23;0.47)	0.92
UL	BWDM	0.0032 (0.0018;0.0068)	–	–	1
	ExpoM	0.00028 (0.00013;0.00059)	−0.0025 (−0.0062;−0.0015)	0.083 (0.027;0.18)	0.40
	EmeSpy	0.00027 (0.00022;0.00036)	−0.0021 (−0.0058;−0.0013)	0.12 (0.061;0.16)	0.64
DECT	BWDM	0.029 (0.0081;0.095)	–	–	1
	ExpoM	0.0012 (0.00019;0.009)	−0.017 (−80.055;−0.0047)	0.16 (0.05;0.4)	0.58
	EmeSpy	0.001 (0.00045;0.0027)	−0.0015 (−0.002;−0.0012)	0.19 (0.09;0.34)	0.59
WIFI	BWDM	0.0022 (0.0016;0.0029)	–	–	1
	ExpoM	0.00039 (0.00017;0.00089)	−0.018 (−0.051;−0.0018)	0.054 (0.027;0.13)	0.72
	EmeSpy	0.00015 (0.000083;0.00032)	−0.0017 (−0.0024;−0.0013)	0.056 (0.044;0.17)	0.1

Table 2 includes 447 measurements from 261 microenvironments for the comparison of the ExpoM with the BWDM, and 104 measurements from 78 microenvironments for the comparison of the EmeSpy with the BWDM. Columns “difference”, “ratio” and “rho” (Spearman correlation coefficient) compare the exposimeter with the BWDM, respectively. DL = Downlink, UL = Uplink, IQR = interquartile range: 50th (25th; 75th) percentile.

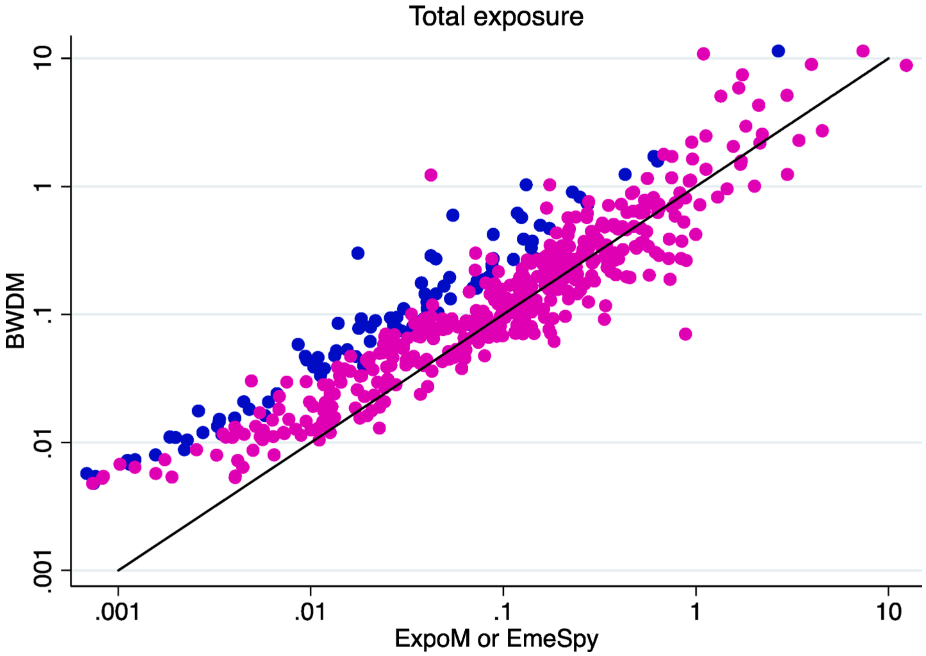

Fig. 1. Total ExpoM and EmeSpy exposure vs BWDM exposure *Scatter plot of geometric means per microenvironment measured with ExpoM (magenta dots) or EmeSpy (blue dots) compared to measurements taken with the BWDM. The black line denotes y = x. Values are in mW/m^2 and correspond to all frequency bands that are common to the three devices.* (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4. Discussion

We compared microenvironmental outdoor and indoor RF-EMF measurements taken with exposimeters as they have been frequently employed in epidemiological studies with a newly developed BWDM. Results indicate that – compared to measurements taken with the BWDM – commercially available exposimeters worn on-body estimate somewhat lower total and downlink exposure (only EmeSpy) but clearly result in lower uplink, DECT and WiFi exposure. These differences were observed across the whole exposure range and not restricted to either low or high values. In addition, exposures were lower when measured with the EmeSpy as compared to when using the ExpoM. Nevertheless, because observed total exposure was strongly determined by downlink exposure, the introduced absolute error was relatively small: Across simultaneously measured microenvironments, the median difference of total RF-EMF exposure of the ExpoM vs BWDM was −0.01 mW/m^2 and for the EmeSpy vs the BWDM was −0.06 mW/m^2. Spearman correlation coefficients showed that ranking was similar across all devices for total and downlink exposure.

Strengths of our approach include that the novel BWDM was calibrated on-body of all assistants who performed measurements, the collection of simultaneous measurements with BWDM and two commercially available exposimeters and that we followed the same measurement protocol in five countries. Assistants were instructed not to use their own mobile phones or other electronic devices, which means that uplink and WiFi exposure pertained to use of devices in the vicinity of the assistants and mostly far-field exposure conditions as for all other measured bands. It also means that our measurements are not informative regarding uplink or WiFi exposure from the own use of a mobile device. Our assessment targets several of the previous major challenges

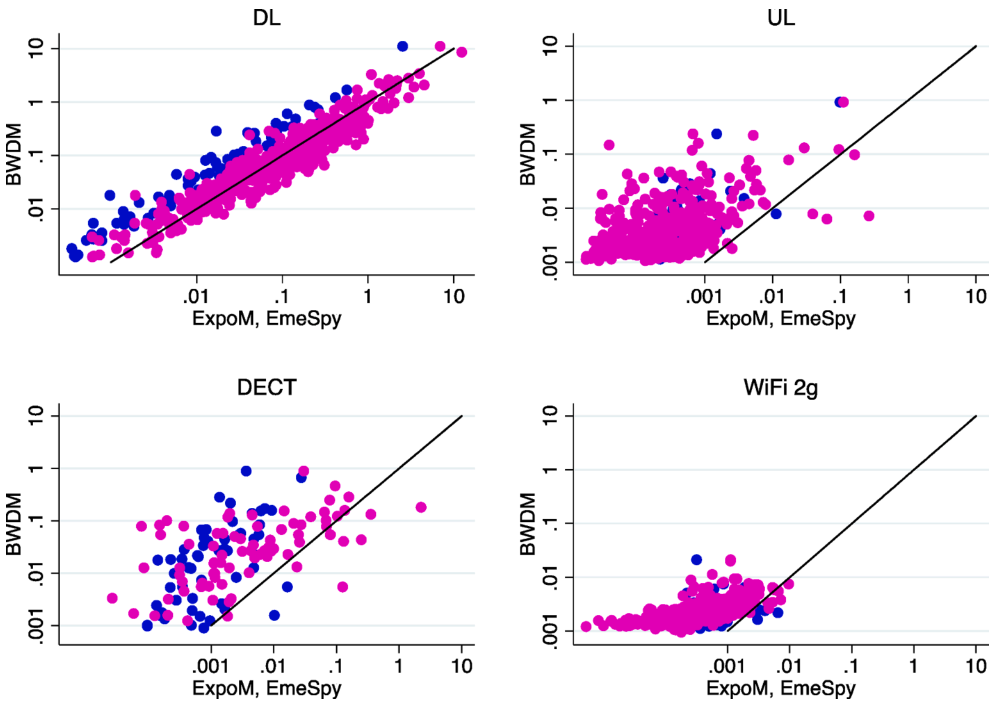

Fig. 2. Downlink, uplink, DECT and WiFi2G ExpoM-RF and EmeSpy exposure vs BWDM exposure *Scatter plots of microenvironments' geometric means with ExpoM (magenta dots) and EmeSpy (blue dots) compared to measurements taken with the BWDM. Values are in mW/m^2 and correspond to all overlapping frequency bands. The black line denotes $y = x$. Top left panel: Downlink exposure (DL); top right panel: Uplink exposure (UL). Bottom left panel: DECT exposure, bottom right panel: WiFi 2 g exposure.* (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

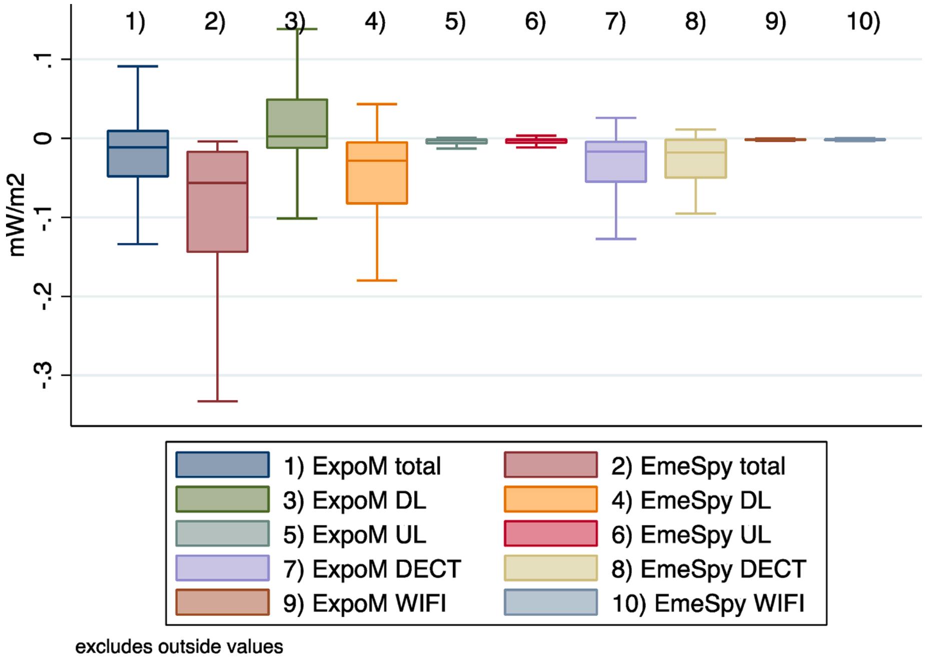

Fig. 3. Box plots of absolute differences of geometric mean levels per microenvironment, comparing exposimeter minus BWDM measurements for different exposure categories *Total = total exposure, DL = Downlink, UL = Uplink, DECT = cordless landline phone. WiFi = WiFi 2.4G. For better visibility, outliers were removed.*

when using exposimeters and which have been previously discussed in the scientific literature (Bolte, 2016), in particular on body calibration, using antennas with optimized placing to prevent body shielding, and a short measurement logging interval. Our study indicates that exposure levels obtained from a single exposimeter are lower than BWDM measurements derived from two antennas placed on diametrically opposite locations on the body, which is compatible with the effects of body shielding. In addition, results indicated that logging intervals as such did not have a major impact on averaged exposure levels.

Limitations include that the developed BWDM was bulky and heavy (about 4 kg) and too inflexible to e.g. sit down during measurements. Further, the device needs to be calibrated for each individual to account for different body proportions. Due to these constraints, all measurements took preparation time in the overall logistics. This means that applicability in a usual study setting with general population study participants would be impossible. A future possible solution for this problem could be to integrate the separate nodes in two miniaturized exposimeters worn at opposite sides on the body, although such a device would need to be developed first.

Our comparison of the BWDM with ExpoM and EmeSpy measurements does not expand to other meters that have been previously applied in epidemiological settings, such as the Spy 120, 140, the TS/

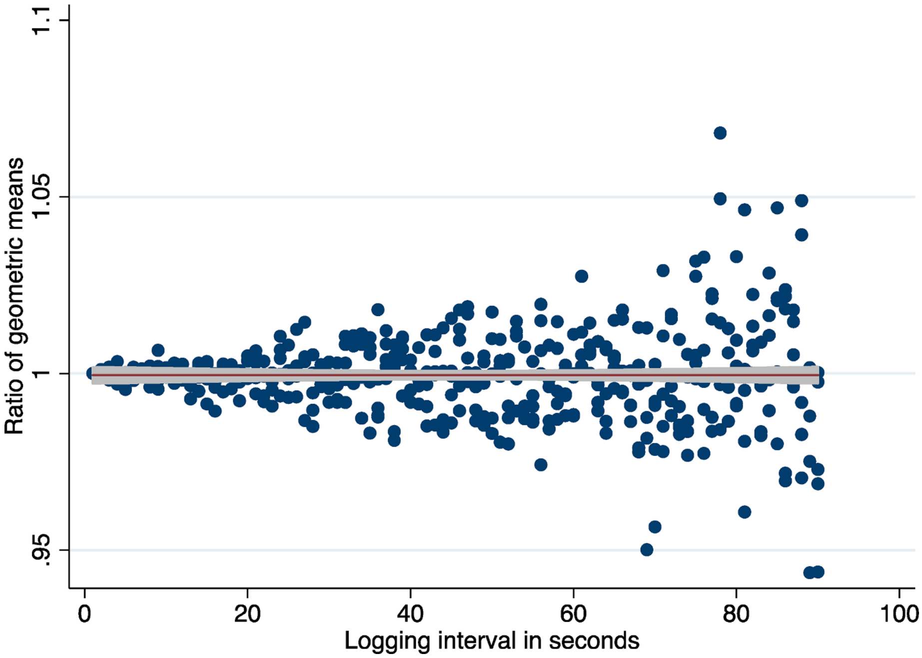

Fig. 4. Comparison of artificially increased logging intervals using total exposure as measured by BWDM *Scatter plot of ratios of geometric mean levels as measured with the BWDM. We compared artificially generated increasing logging intervals from 2 to 90 s and compared to taking a measurement every 1 s. Shown here are ratios of geometric means. Ratios were calculated separately for each countrys' data set. The red line shows the fitted regression line and the grey area the corresponding confidence interval.* (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

001/UB Taoma or the Maschek (Frei et al., 2010; Calvente et al., 2016; Thomas et al., 2008). Another limitation is that frequency bands included in all three devices are not identical. Therefore, comparisons were limited to overlapping frequency bands. This would mean that true total RF-EMF exposure would be higher, especially since broadcast bands were not included in the comparisons. However, plotting total exposure as assessed from all three devices, independent of the captured frequency bands, shows a similarly good match as when plotting only total exposure of overlapping bands, with high correlation coefficients and only slightly differing exposure levels (supplemental Figure SF4), indicating that the overlapping frequency bands covered the most relevant exposure contributions.

RF-EMF limit guidelines such as those developed by ICNIRP 2020 (International Commission on Non-Ionizing Radiation, 2020) provide reference levels (electric fields or power densities) that aim at protecting humans against adverse health effects of exposure to RF-EMFs. These reference levels are determined for free space (actual fields) so in the absence of a body. To overcome this problem, the BWDM used in this study was calibrated on the body, using a comparison of the fields measured on the body to the actual fields measured in absence of the body, resulting in a calibration factor per frequency band/subject (Aminzadeh et al., 2018; Aminzadeh et al., 2019; Aminzadeh et al., 2016). This resulted in a shown high accuracy of the BWDM in the range of 1.2–3.6 dB for the different subjects and across the measured frequency bands (Aminzadeh et al., 2018). Nevertheless, a problematic band for all devices seems to be DECT, where cross-talk can occur between neighboring bands, especially with the 1800DL band (Aminzadeh et al., 2019). In our assessment, we did not impute DECT values below the LoQ but set them to missing. Methods such as robust ordered regression use the distribution of quantified exposure to impute values below the detection limit (Roosli et al., 2008). We refrained from this procedure due to the expected uncertainty of all observed measurement values. If measurement values below LoQ indeed represent low or absent exposure, then omitting these values from our analysis may have introduced some degree of overestimation of DECT exposure. Please note, however, that the contribution of DECT to total exposure was still low. A future possible improvement of the BWDM expands to shielding the nodes and using narrow-band filters to reduce inaccuracies introduced by crosstalk. It is unclear if such an improvement could also be implemented in the exposimeters. For a longer term perspective, DECT phone use is steadily decreasing over time (Union, 2019) and therefore, its contribution to total RF-EMF exposure is likely to further decrease over time, but cross-talk may become an issue in other frequency bands such as 3.6 GHz currently implemented for 5G.

As such, our comparison shown here was not intended to reflect average exposure of populations. Nevertheless, exposure ranges are in line with earlier reports summarizing mobile microenvironmental exposures (Jalilian et al., 2019; Sagar et al., 2018). In particular, Jalilian et al. reported downlink exposures to be the major contributor to outdoor total exposures, with percentages between 61 and 99% of total RF-EMF exposure originating from downlink signals. Uplink signals contributed less than 1% and were judged to be negligible (Jalilian et al., 2019). In the transportation system, this review found very low uplink contribution in train stations, moderate contribution in trams and busses and predominant contribution in trains. Thus, any underestimation of uplink signals in previous studies, in addition to neglecting the LTE800 and LTE2600 uplink bands, would not greatly change this assessment for outdoor settings. In transport settings, however, previous studies may have underestimated uplink exposure.

5. Conclusion

Our device comparisons are informative for the interpretation of existing epidemiological research results and may help future studies regarding how to design improved exposure assessment strategies and how to interpret RF-EMF exposure values reported in the scientific literature. Overall, within the currently applied frequency bands, our study indicates that using one single exposimeter results in slightly lower exposures than measured by a BWDM, most likely due to body shielding, but rank exposure levels reliably. Body shielding could probably at least be in part mitigated by using two exposimeters, on opposite sides of the body (Bhatt et al., 2016). Given their easier handling and relatively compact size, exposimeters thus represent valuable tools to assess population exposure to RF-EMF.

CRediT authorship contribution statement

Anke Huss: Methodology, Writing - review & editing, Conceptualization, Formal analysis, Writing - original draft. **Stefan Dongus:** Methodology, Writing - review & editing, Investigation, Data curation.

Reza Aminzadeh: Methodology, Writing - review & editing, Resources, Investigation, Data curation. **Arno Thielens:** Methodology, Writing - review & editing, Resources. **Matthias den Bossche:** Methodology, Writing - review & editing, Resources. **Patrick Van Torre:** Methodology, Writing - review & editing, Resources. **René Seze:** Methodology, Writing - review & editing. **Elisabeth Cardis:** Methodology, Writing - review & editing. **Marloes Eeftens:** Methodology, Data curation, Formal analysis, Writing - review & editing. **Wout Joseph:** Methodology, Conceptualization, Resources, Writing - review & editing, Resources. **Roel Vermeulen:** Methodology, Writing - review & editing. **Martin Röösli:** Methodology, Conceptualization, Writing - review & editing.

Declaration of Competing Interest

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

Acknowledgement

Grant Sponsors: This research was funded by the National Research Program of the French Agency for Food, Environmental and Occupational Health and Safety (ANSES), grant No 2015-2-RF-07, and the equipment was supported by funding from the European Commission Seventh Framework Programme under grant agreement number FP7 603794 (GERoNiMO). Our funders had no involvement in the study design; data collection, analysis and interpretation of data; in the writing of the report; and in the decision to submit the article for publication.

A.T. is a postdoctoral fellow of the Research Foundation Flanders (FWO) under grant agreement no. 12U1417N.

ISGlobal also acknowledges support from the Spanish Ministry of Science, Innovation and Universities through the “Centro de Excelencia Severo Ochoa 2019-2023” Program (CEX2018-000806-S), support from the Generalitat de Catalunya through the CERCA Program and support from the Secretariat of Universities and Research of the Department of Business and Knowledge of the Generalitat of Catalonia through AGAUR (the Catalan Agency for Management of University and Research Grants) (Project 2017 SGR 1487).

We’d like to thank the research assistants for collecting the data. We’d also like to thank the police departments in the measurement cities for advice and support of this study.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2021.106711.

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