Between-Country Comparison of Whole-Body SAR From Personal Exposure Data in Urban Areas

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In five countries (Belgium, Switzerland, Slovenia, Hungary, and the Netherlands), personal radio frequency electromagnetic field measurements were performed in different microenvironments such as homes, public transports, or outdoors using the same exposure meters. From the mean personal field exposure levels (excluding mobile phone exposure), whole-body absorption values in a 1-year-old child and adult male model were calculated using a statistical multipath exposure method and compared for the five countries. All mean absorptions (maximal total absorption of 3.4 μW/kg for the child and 1.8 μW/kg for the adult) were well below the International Commission on Non-Ionizing Radiation Protection (ICNIRP) basic restriction of 0.08 W/kg for the general public. Generally, incident field exposure levels were well correlated with whole-body absorptions (SAR_{wb}), although the type of microenvironment, frequency of the signals, and dimensions of the considered phantom modify the relationship between these exposure measures. Exposure to the television and Digital Audio Broadcasting band caused relatively higher SAR_{wb} values (up to 65%) for the 1-year-old child than signals at higher frequencies due to the body size-dependent absorption rates. Frequency Modulation (FM) caused relatively higher absorptions (up to 80%) in the adult male. Bioelectromagnetics © 2012 Wiley Periodicals, Inc.

Key words: radio frequency electromagnetic fields (RF-EMF); exposimeter; personal exposure; whole-body absorption; specific absorption rate (SAR); RF measurement; exposure of general public

INTRODUCTION

Personal radio frequency electromagnetic field (RF-EMF) exposure of the general public is assessed nowadays using personal exposure meters (exposimeters). Several countries have performed separate measurement studies and various results have been published [Bolte et al., 2008; Joseph et al., 2008; Röösli et al., 2008; Thomas et al., 2008a,b; Thuróczy et al., 2008; Frei et al., 2009; Viel et al., 2009]. Röösli et al. [2010] and Mann [2010] discussed measurement protocols for exposimeters and personal exposure measurements. In Joseph et al. [2010b],

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mean field strength levels obtained from personal RF-EMF measurements in different real environments (called microenvironments in this article) were compared between urban areas in five European countries by applying the same data analysis methods. From a biological perspective, absorbed radiation may be more relevant than the electric field occurring at the body surface (incident field). Thus, Joseph et al. [2010a] proposed a method to calculate whole-body specific absorption rates (SAR_{wb}) from personal exposimeter data for different human spheroid phantoms. Single plane-wave exposure for different phantoms and frequencies have been discussed by Dimbylow [2002], Joseph and Martens [2003], Wang et al. [2006], Conil et al. [2008], Dimbylow et al. [2008], Vermeeren et al. [2008b], Kühn et al. [2009], and Uusitupa et al. [2010]. These studies showed that the SAR depends very much on the type of phantom, anatomy, and posture. Vermeeren et al. [2008a,b] and Joseph et al. [2010a] determined absorption in real environments using a statistical multipath exposure method.

The objective of this article is to compare and calculate the SAR_{wb} for a child and adult model in five countries (Belgium, Switzerland, Slovenia, Hungary, the Netherlands) for different wireless signals, based on the mean exposure levels measured with personal exposimeters in different microenvironments that were published by Joseph et al. [2010b]. For this purpose, the pooled data from the countries are combined and the method of Joseph et al. [2010a] is applied to determine the actual whole-body SAR in the human phantom.

This article is the first one where a comparison of SAR_{wb} (for child and adult models) based on personal exposure between different countries is made, and it enables the field exposure situation to be compared with the actual absorption in real circumstances. In most epidemiological studies, exposure is characterized using measured field strengths, and the results of this study give more insight into how well actual mean absorption is represented by the average field strengths.

MATERIALS AND METHODS

Microenvironments

Five typical microenvironments for the general public were defined in order to enable a comparison between the different countries. The five microenvironments are denoted with a short name of the form: ''location–environment–time'': (i) outdoor–urban–day, (ii) indoor–office–day, (iii) indoor–train–day, (iv) indoor–car/bus–day, (v) indoor–urban home–day/night. Details are provided in Joseph et al. [2010b]. To minimize heterogeneity among the studies, urban areas are defined as areas with more than 400 persons per square km, and offices as working places of employees working at desks. Daytime and nighttime are here defined with respect to working hours: ''daytime'' is defined as the period from 6 am to 6 pm (working hours) and ''nighttime'' as the period where most people do not work or are sleeping, thus the period after 6 pm and before 6 am. Table 1 lists the considered microenvironments.

Measurements in Participating Countries

In each of the countries, electric field measurements were performed using an isotropic personal exposimeter (Model DSP90-120-121 EME Spy, SATIMO, Courtaboeuf, France). The exposimeter measures 12 frequency bands: Frequency Modulation (FM); television (TV); digital radio or Digital Audio Broadcasting (DAB); Terrestrial Trunked Radio (TETRA); Global System for Mobile Communications at 900 MHz (GSM900): downlink (DL; i.e., communication from base station to mobile phone) and uplink (UL; i.e., communication from mobile phone to base station), GSM at 1800 MHz (GSM1800) down and uplink; Digital Enhanced Cordless Telecommunications (DECT); Universal Mobile Telecommunications System (UMTS) down and uplink; and wireless Ethernet for wireless local area networks (WiFi). The measurement procedures and number of samples and subjects are summarized in Joseph et al. [2010b]. The measurements were performed in the period from 2007 to 2009. In the

TABLE 1. Considered Microenvironments for Comparison

Logical name	Microenvironment	Description
Out–urban	Outdoor–urban–day	Outdoor walking, standing, sitting in an urban environment during the daytime with >400 persons/km^2
Office	Indoor–office–day	Office environment (employees)
Train	Indoor–train–day	Exposure in train
Car/bus	Indoor–car/bus–day	Exposure in car or bus (driving)
Urban–home	Indoor–urban home–day/night	In home in an urban area with >400 persons/km^2

studies of Belgium and the Netherlands, measurements were performed on hired staff whereas the studies of Switzerland, Slovenia, and Hungary were based on volunteers from a population sample. The exposimeters were calibrated on a regular basis and described in the studies of the participating countries [Bolte et al., 2008, 2011; Joseph et al., 2008; Thuróczy et al., 2008; Frei et al., 2009].

Procedure and Data Analysis

Figure 1 shows a flow chart of the procedure used to compare the data from the different countries and to convert the data to SAR_{wb}. The procedure consisted mainly of three steps. Firstly, exposimeter data were collected from the different national studies. The robust regression on order statistics (ROS) method was used to compute mean exposure levels [Röösli et al., 2008] (Fig. 1). Secondly, a human body model was selected; and thirdly, SAR_{wb} in the phantom was calculated for the mean power density using the statistical tool of Vermeeren et al. [2008a,b] and the method proposed by Joseph et al. [2010a], and was compared for the different countries.

Field Data Analysis

In all countries, all the measurements taken in each microenvironment were combined and analyzed (step 1 in Fig. 1). Since a large proportion of the measurements was censored, that is, below the lower detection limit of the exposimeter (0.0067 mW/m^2), we applied the ROS method proposed by Röösli et al. [2008] to determine the mean values of the power density S (mW/m^2) for each microenvironment. Exposimeter data of all participating countries were processed in exactly the same way using the ROS algorithm with statistical software R (www.r-project.org), which is discussed in detail in Helsel [2005].

The total exposure S_{tot} (mW/m^2) was calculated by summing up the mean power density values of all frequency bands:

$$S_{tot} = \sum_i S_i \quad (\mathrm{W/m^2}) \tag{1}$$

where S_{tot} is the total power density of all signals, and S_i is the power density for each source at its specific frequency i (different sources are considered).

Selection of Human Phantoms

An appropriate human phantom had to be selected (step 2 in Fig. 1). We selected a spheroid human body model because this simple model gives a realistic estimation of the SAR_{wb} [Durney et al., 1986]. The homogeneous tissues of the spheroid human body phantoms were assigned the dielectric properties tissues suggested by the International Electrotechnical Commission (IEC) Standard 62209 [IEC, 2005] for compliance testing for the different frequencies. Here, we investigated the adult male phantom and the 1-year-old child phantom (highest whole-body absorptions are obtained for this phantom as explained in Joseph et al. [2010a]). The sizes of these phantoms were taken from Durney et al. [1986].

Calculation of the Whole-Body SAR and Comparison

In a realistic exposure environment exposure to EMF is constantly changing. Consequently, a single measured incident field value can be caused by different exposures (i.e., combinations of incident plane waves). Hence, for a single measured incident

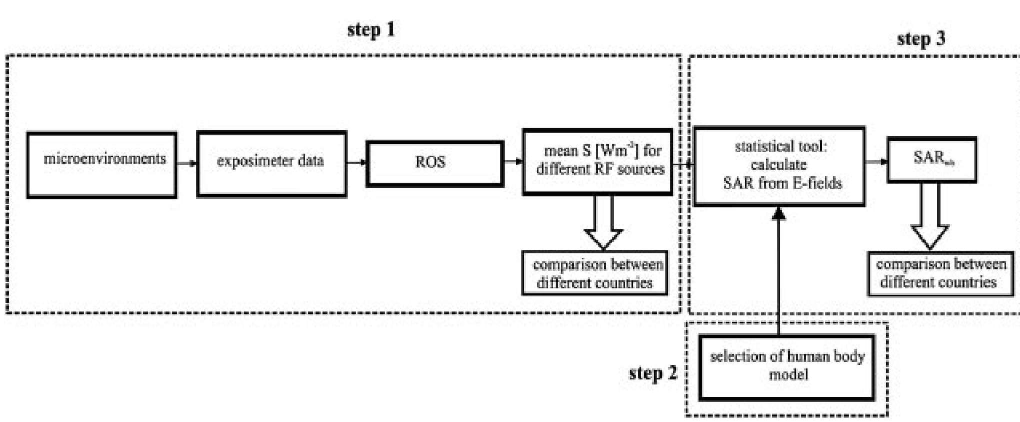

Fig. 1. Flow chart of the procedure to determine and compare SAR_{wb} between countries (ROS = robust regression on order statistics).

field value a distribution of SAR_{wb} values exists. Estimation of the SAR_{wb} from measured incident field values is based on the statistical tool of Vermeeren et al. [2008a,b] and is extensively described by Joseph et al. [2008, 2010a]. This method is applied in this work to calculate the distribution of the SAR_{wb} values in a child and an adult human body model for every measured incident field value at the corresponding communication frequency (5000 realistic exposure samples are generated to obtain statistically relevant results; step 3 in Fig. 1). From the SAR_{wb} distribution, the mean SAR_{wb} value is determined. Next, the parameters of the relationship between mean SAR_{wb} values and the measured incident electric field samples are obtained by performing minimum least-square error fits of the following relation between SAR_{wb} and E [Joseph et al., 2010a]:

$$\langle \mathrm{SAR_{wb}} \rangle_i = a \times (\langle E \rangle)_i^2 = a \times 377 \times \langle S \rangle_i \quad (\mathrm{W/kg}) \tag{2}$$

where $\langle \mathrm{SAR_{wb}} \rangle_\mathrm{i}$ represents the mean value of the whole-body SAR at frequency i, and parameter a ($m^2/(\Omega kg)$) depends on the type of phantom, the different frequencies, and the type of environment [Joseph et al., 2010a]. E represents the electric field (V/m) and S the power density (W/m^2); $\langle . \rangle_i$ denotes mean values for a source at its specific frequency i. Here, we calculated the mean SAR_{wb} from the mean power densities $\langle S \rangle$ provided by each country for the different microenvironments.

The SAR_{wb} was determined for 9 RF sources out of the 12 frequency bands measured by the exposimeter: 100 MHz (FM), 200 MHz (TV/DAB), 400 MHz (TETRA), 600 MHz (TV), 950 MHz (GSM900 DL), 1850 MHz (GSM1800 DL), 1900 MHz (DECT), 2150 MHz (UMTS), and 2450 MHz (WiFi). For uplink (GSM900 UL, GSM1800 UL, and UMTS UL), SAR_{wb} was not determined because personal exposure measurements do not allow differentiation between uplink from the personal phone producing localized exposure and uplink from other people's phones producing a generally more homogenous whole-body exposure. Without such a differentiation, SAR_{wb} calculations would not be reliable.

Appropriate environments have to be selected when calculating SAR_{wb} [Vermeeren et al., 2008a; Joseph et al., 2010a]. For urban–outdoor, the "urban macro/micro-cell environment" was selected for the statistical tool for all sources (i.e., outdoor sources) except for WiFi and DECT, where the "outdoor–indoor environment" was chosen because WiFi and DECT are mainly located inside houses and buildings. For office, train, car/bus, and urban–home (indoor sources) the "outdoor–indoor environment" was selected for all sources except WiFi and DECT, where the "indoor pico-cell environment" was selected.

The total SAR_{wb} values due to the considered sources (88–2450 MHz) were determined and compared to the International Commission on Non-Ionizing Radiation Protection (ICNIRP) limit of 0.08 W/kg for the general public. They were calculated as [ICNIRP, 1998]:

$$\mathrm{SAR_{wb}}|_{\mathrm{total}} = \sum_{i=100\,\mathrm{MHz}}^{2450\,\mathrm{MHz}} \mathrm{SAR_{wb}}|_i \quad (\mathrm{W/kg}) \tag{3}$$

where $\mathrm{SAR_{wb}}|_{\mathrm{total}}$ and $\mathrm{SAR_{wb}}|_i$ are the total whole-body SAR and the whole-body SAR for each source at its specific frequency i (nine sources are considered), respectively.

Values for Parameter *a* per Phantom, Frequency, and Environment

Figure 2 shows the parameter a from Equation (2) for mean SAR_{wb} values of the 1-year-old child and adult male for the different environments (urban–macro-cell, indoor–outdoor, indoor pico-cell). The value of parameter a equals the value of SAR_{wb} for an incident electric field of 1 V/m (power density of 1/377 W/m^2). Thus, Figure 2 provides the SAR_{wb} values for normalized incident fields. The parameter a depends on the frequency, posture, and size of the human body model. Obviously, parameter a is higher for the child than for the adult phantom due to its smaller dimensions, as clearly shown in Figure 2. For both phantoms, the whole-body absorption decreases with increasing frequencies. For the 1-year-old child, absorption is highest at about 200 MHz, while for the adult phantom it is highest at about 73 MHz [Durney et al., 1986].

Method for Ranking Environments for Mean SAR_{wb} and Power Densities

To compare which microenvironment causes the highest absorptions and the highest (incident) power densities (S), we normalize SAR_{wb} and S as follows:

$$\overline{\mathrm{SAR_{wb}}}(c,e,b) = \frac{\mathrm{SAR_{wb}}(c,e,b)}{\max\limits_{\substack{e \in \mathrm{all\ env} \\ b \in \mathrm{all\ bodies}}} (\mathrm{SAR_{wb}}(c,e,b))} \tag{4}$$

where $\overline{\mathrm{SAR_{wb}}}(c,e,b)$ (c = country, e = environment, nment, and b = body model) denotes the normalized

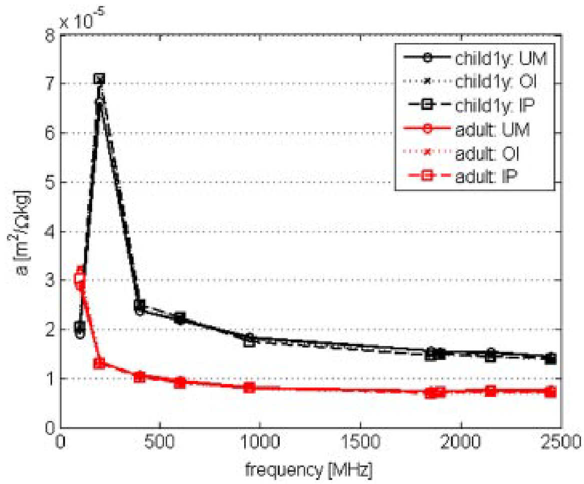

Fig. 2. Parameter *a* for 1-year-old child and adult male model (mean SAR_{wb} values) for different environments. UM: urban–macro-cell, OI: outdoor–indoor, IP: indoor pico-cell (the value of *a* corresponds with the value of SAR_{wb} for an incident field strength of 1 V/m).

total SAR_{wb} due to a RF source for each country (in interval [0, 1]), *all env* denotes all environments, and *all bodies* denotes the considered 1-year-old child phantom and the adult male phantom. And:

$$\overline{S}(c,e) = \frac{S(c,e)}{\max\limits_{e \in \text{all env}} (S(c,e))} \quad (5)$$

where $\overline{S}(c,e)$ is the normalized incident power density due to a RF source for each country (in interval [0, 1]). These quantities will enable comparison of the ranking of absorptions and power densities in the different environments.

Validation of the Applied Methods

Several validations have been conducted for the steps used in the procedure described in this article. The statistical multipath tool has been validated in several journal papers [Vermeeren et al., 2008a,b] and compared with finite-difference time-domain (FDTD) simulations as a validation. Deviations of less than 1% for the SAR_{wb} were obtained. The ROS method for calculation of mean values from exposimeter measurements has been shown to produce reliable results of personal measurements with a substantial proportion of nondetects [Röösli et al., 2008]. The combination of exposimeter data as input to the statistical tool has been validated in Joseph et al. [2010a]. Both parameters *a* and *b* were fitted (as a validation) in Equation (1) from Joseph et al. [2010a], describing the relation between the SAR and electric field. As shown in Table 3 of Joseph et al. [2010a], a value of *b* equal to 2 was obtained for all the fits, as expected. Here, we use $b = 2$ in Equation (2), (shown as an exponent), because we know this is the value for the relation between SAR and *E*. Propagation analysis and the application of statistical distributions per environment is a known approach as well. Propagation analysis is, in practice, done according to the type of environment [Oestges and Clerckx, 2007; Tanghe et al., 2008] and propagation models are provided for different types of environments (office, urban, rural, etc.). So, we assumed the same parameters and same distribution types for all home environments in the different countries, for example (similar for other environments).

RESULTS

SAR for Different Environments and Countries

Figure 3a,b summarizes the total mean SAR_{wb} values for all the microenvironments and countries for the 1-year-old child and adult male model, respectively. The same scale is used in both figures to enable easy comparison. All mean absorptions in Figure 3 satisfied the ICNIRP basic restriction of 0.08 W/kg for all considered environments and countries [ICNIRP, 1998], which is the basis for exposure limits in the considered countries. Some countries have more restrictive limits with respect to field strength values: in Flanders, Belgium, for example (four times lower than the ICNIRP guidelines and additionally 3 V/m at 900 MHz) and for specific situations in Slovenia and Switzerland (10 times lower than the ICNIRP guidelines at places of sensitive use (homes and offices)).

Absorptions were of the same order of magnitude in all countries. Total mean absorptions in the adult phantom (Fig. 3b) were lower than for the 1-year-old child (Fig. 3a) because of the larger dimensions of the adult. The highest total mean SAR_{wb} values (for mean exposure) were obtained in a Belgian office and were 3.4 μW/kg for the child and 1.8 μW/kg for the adult male.

Other microenvironments with relatively higher whole-body absorptions (>1 μW/kg) were outdoor–urban in Belgium and the Netherlands, and car/bus in Slovenia and Hungary (Fig. 3). Lowest whole-body absorptions occurred in urban homes in all countries.

Ranking of Environments for Mean SAR_{wb} and Power Densities

Figure 4 compares the ranking of each environment for the normalized quantities ($\overline{SAR_{wb}}(c,e,b)$

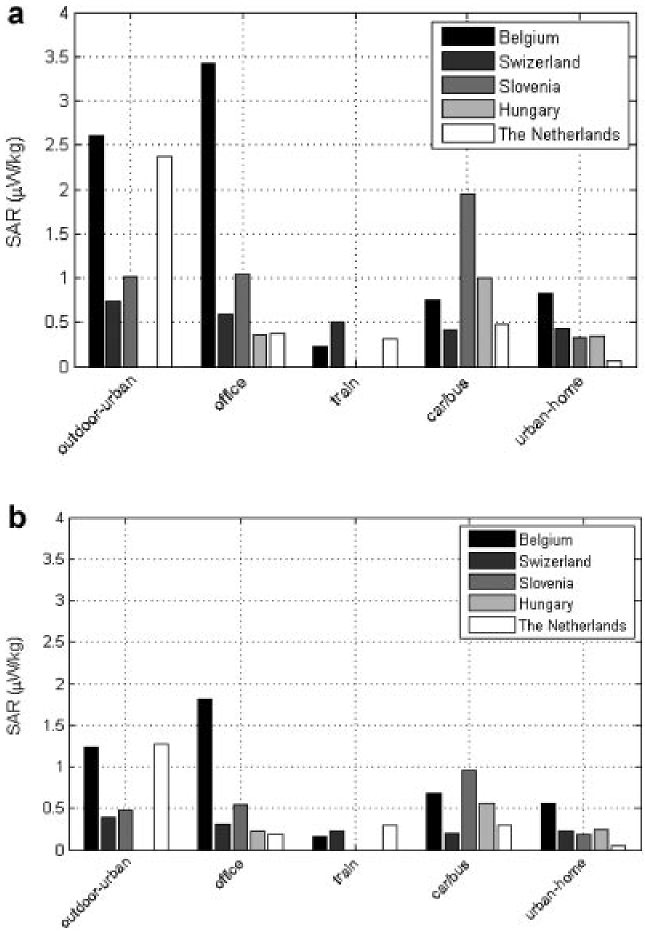

Fig. 3. Mean total whole-body absorptions (μW/kg) in (**a**) the 1-year-old child model and (**b**) the adult male model for all considered microenvironments in all countries (no data are available for trains in Slovania and Hungary and for outdoor–urban in Hungary).

and $\overline{S}(c, e)$) per country for both phantoms. This figure enables the ranking of environments per country with respect to the SAR for both phantoms (black and gray bars; there was no train info for Slovenia and Hungary and no info for outdoor–urban areas in Hungary because no or too few measurements were taken in these microenvironments [Joseph et al., 2010b]) and comparison of this ranking with the one of the incident power densities measured with the exposimeter (white bars, excluding uplink). In general, the ranking of SAR_{wb} for the five microenvironment in each country was equal to the ranking of the total power densities (S_{tot}). However, exceptions occur; for instance, in Belgium the highest absorptions were found in offices, contrary to the highest power densities in outdoor–urban environments. The total mean absorption in the 1-year-old child is higher than the absorption in the adult (black bars vs. gray bars in Fig. 4).

Contribution of RF Sources

Table 2 lists the SAR_{wb} in the 1-year-old child for all sources, environments, and countries. Table 3 lists the corresponding absorptions for the adult male. The highest SAR_{wb} values for the 1-year-old were obtained in Belgium for TV/DAB (200 MHz) in offices and GSM DL in outdoor–urban environments (about 2.2 μW/kg). Higher SAR_{wb} values again corresponded with the higher power densities $\langle S \rangle$ given in Joseph et al. [2010b] (e.g., for outdoor–urban, 0.33 mW/m^2 for downlink in Table 4 of Joseph et al. [2010b] corresponded with 2.2 μW/kg for GSM900 DL in this study) but also depended on the frequency of the signal and dimensions of the phantom. For the adult model, the highest values were obtained for FM (100 MHz) in offices (1.2 μW/kg in Belgium), trains (0.2 μW/kg in the Netherlands), car/bus (0.5 μW/kg in Belgium), and homes (0.4 μW/kg in Belgium).

For FM and TV/DAB, relatively lower power densities were obtained in Joseph et al. [2010b] but due to the frequency of the signal and the dimensions of the phantom, relatively higher SAR_{wb} values are observed for the 1-year-old phantom (Table 2). This effect is also present for the adult male phantom for FM (100 MHz; Table 3) but less pronounced because of its larger dimensions.

Figure 5 shows the contribution of the different sources to the total SAR_{wb} in the five microenvironments for all countries for the 1-year-old child and the adult male. In all microenvironments, absorption to downlink mobile telecommunication was important and clearly dominates for outdoor–urban environments (>65%). FM radio absorptions were present in all countries (typically 10% or higher for the 1-year-old child) and were important for adults in urban–homes, office, car/bus, and trains. For both the SAR and incident power density, contributions from mobile telecommunication signals were important in all environments [Joseph et al., 2010b].

DISCUSSION

Our study compares the mean whole-body absorptions in two phantoms and the contributions of RF sources in five relevant microenvironments in different European countries (Belgium, Switzerland, Slovenia, Hungary, and the Netherlands). Mean absorptions were generally far below the standard limits and the ranking of mean absorptions was very

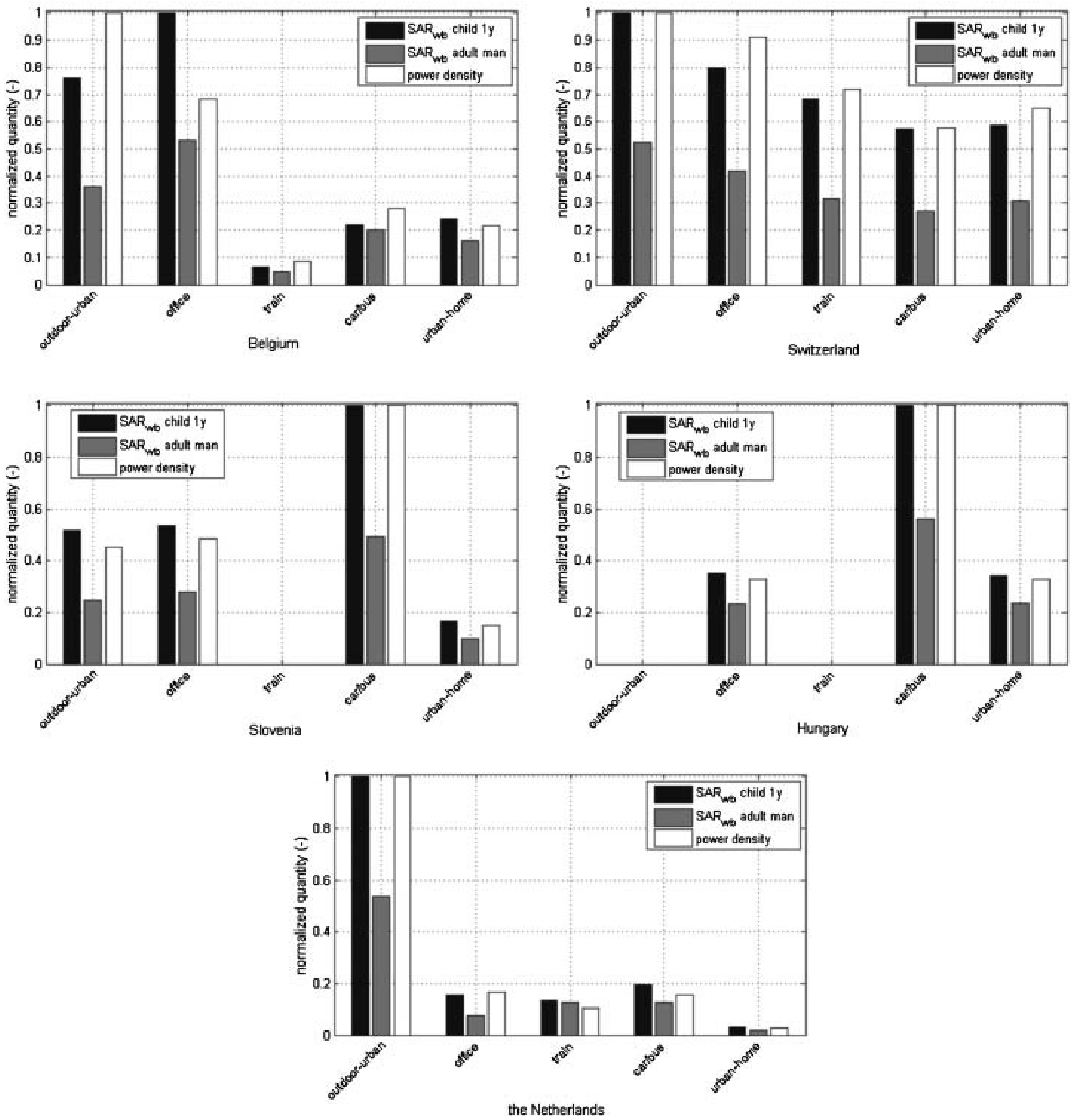

Fig. 4. Whole-body absorptions (1-year-old child and adult male) normalized to the maximum SAR of each country and incident power density normalized to the maximum *S* of each country for all considered microenvironments (no data are available for trains in Slovania and Hungary and for outdoor–urban in Hungary).

similar to that of the mean field strengths measured by the exposimeters.

Strengths and Limitations

This article is the first one where a comparison of absorptions in phantoms with personal RF-EMF exposure data in real environments in urban areas in different countries is made. The proposed methodology combined with the application of a statistical multipath exposure method enabled us to compare whole-body absorptions from exposimeter data in different countries. In a realistic environment, electromagnetic waves travel along multiple paths. It is obvious that the homogeneous exposure of a single plane wave is not representative of the multipath exposure in a realistic environment. Therefore, to assess the statistics of the absorption correctly and correlate it with the incident field levels, the method of Vermeeren et al. [2008a] was used. Although the measurements were performed solely on adults, we

TABLE 2. Mean SAR Values (μW/kg) in the 1-Year-Old Child Corresponding With Mean Exposures *S* (mW/m^2) for All Microenvironments and All Countries

Microenvironment	Country	FM	TV/DAB	TETRA	TV	GSM900 UL	GSM900 DL	GSM1800 UL	GSM1800 DL	DECT	UMTS UL	UMTS DL	WiFi	Total
Outdoor–urban	Belgium	0.102	0.085	0.022	0.094	—	2.195	—	0.074	0.017	—	0.019	0.001	2.608
	Switzerland	0.050	0.009	0.002	0.135	—	0.194	—	0.295	0.030	—	0.014	0.008	0.739
	Slovenia	0.032	0.007	0.011	0.014	—	0.829	—	0.048	0.061	—	0.002	0.005	1.009
	Hungary	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	Netherlands	0.169	0.028	0.015	0.017	—	0.443	—	1.589	0.051	—	0.065	0.000	2.377
Office	Belgium	0.743	2.235	0.002	0.045	—	0.163	—	0.001	0.138	—	0.001	0.093	3.423
	Switzerland	0.026	0.007	0.006	0.012	—	0.024	—	0.092	0.325	—	0.023	0.074	0.589
	Slovenia	0.065	0.031	0.002	0.002	—	0.591	—	0.005	0.336	—	0.003	0.010	1.047
	Hungary	0.073	0.028	0.010	0.036	—	0.131	—	0.036	0.007	—	0.007	0.022	0.350
	Netherlands	0.006	0.008	0.003	0.003	—	0.002	—	0.021	0.316	—	0.003	0.005	0.366
Train	Belgium	0.057	0.013	0.004	0.006	—	0.100	—	0.026	0.004	—	0.004	0.006	0.221
	Switzerland	0.004	0.007	0.002	0.018	—	0.249	—	0.188	0.011	—	0.014	0.012	0.505
	Slovenia	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	Hungary	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	Netherlands	0.149	0.056	0.003	0.012	—	0.035	—	0.052	0.003	—	0.007	0.000	0.316
Car/bus	Belgium	0.312	0.044	0.003	0.026	—	0.255	—	0.066	0.029	—	0.017	0.001	0.753
	Switzerland	0.012	0.023	0.003	0.026	—	0.178	—	0.140	0.020	—	0.012	0.007	0.422
	Slovenia	0.038	0.007	0.002	0.005	—	0.449	—	0.029	1.406	—	0.001	0.014	1.952
	Hungary	0.101	0.016	0.013	0.020	—	0.662	—	0.074	0.078	—	0.026	0.009	0.998
	Netherlands	0.105	0.112	0.010	0.019	—	0.050	—	0.144	0.006	—	0.013	0.008	0.468
Urban–home	Belgium	0.242	0.359	0.010	0.009	—	0.133	—	0.001	0.001	—	0.001	0.070	0.827
	Switzerland	0.023	0.008	0.006	0.020	—	0.034	—	0.068	0.259	—	0.007	0.009	0.435
	Slovenia	0.040	0.007	0.009	0.009	—	0.157	—	0.005	0.086	—	0.001	0.010	0.325
	Hungary	0.078	0.031	0.015	0.024	—	0.065	—	0.011	0.070	—	0.015	0.032	0.341
	Netherlands	0.012	0.008	0.003	0.003	—	0.005	—	0.014	0.002	—	0.002	0.022	0.070

NA, not available.

FM, Frequency Modulation; DAB, Digital Audio Broadcasting; DECT, Digital Enhanced Cordless Telecommunications; DL, downlink; GSM, Global System for Mobile Communications; GSM900, GSM at 900 MHz, GSM1800, GSM at 1800 MHz; TETRA, Terrestrial Trunked Radio; TV, television; UMTS, Universal Mobile Telecommunications System; UL, uplink; WiFi, wireless Ethernet for wireless local area networks.

TABLE 3. Mean SAR Values (μW/kg) in the Adult Male Corresponding With Mean Exposures *S* (mW/m^2) for All Microenvironments and All Countries

Microenvironment	Country	FM	TV/DAB	TETRA	TV	GSM900 UL	GSM900 DL	GSM1800 UL	GSM1800 DL	DECT	UMTS UL	UMTS DL	WiFi	Total
Outdoor–urban	Belgium	0.155	0.017	0.010	0.040	—	0.961	—	0.035	0.008	—	0.009	0.001	1.236
	Switzerland	0.077	0.002	0.001	0.058	—	0.085	—	0.139	0.015	—	0.007	0.004	0.387
	Slovenia	0.048	0.001	0.005	0.006	—	0.363	—	0.022	0.029	—	0.001	0.003	0.479
	Hungary	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	Netherlands	0.258	0.006	0.007	0.007	—	0.194	—	0.749	0.024	—	0.032	0.000	1.277
Office	Belgium	1.177	0.429	0.001	0.018	—	0.073	—	0.001	0.066	—	0.001	0.048	1.813
	Switzerland	0.041	0.001	0.003	0.005	—	0.011	—	0.043	0.156	—	0.011	0.038	0.309
	Slovenia	0.104	0.006	0.001	0.001	—	0.263	—	0.002	0.161	—	0.001	0.005	0.545
	Hungary	0.115	0.005	0.004	0.015	—	0.058	—	0.017	0.003	—	0.003	0.011	0.233
	Netherlands	0.010	0.002	0.001	0.001	—	0.001	—	0.010	0.152	—	0.002	0.002	0.180
Train	Belgium	0.091	0.002	0.002	0.003	—	0.044	—	0.012	0.002	—	0.002	0.003	0.162
	Switzerland	0.006	0.001	0.001	0.007	—	0.111	—	0.088	0.005	—	0.007	0.006	0.233
	Slovenia	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	Hungary	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	Netherlands	0.235	0.011	0.001	0.005	—	0.015	—	0.024	0.002	—	0.003	0.000	0.297
Car/bus	Belgium	0.494	0.008	0.001	0.011	—	0.113	—	0.031	0.014	—	0.008	0.001	0.681
	Switzerland	0.019	0.004	0.001	0.010	—	0.079	—	0.066	0.010	—	0.006	0.004	0.200
	Slovenia	0.060	0.001	0.001	0.002	—	0.199	—	0.014	0.676	—	0.001	0.007	0.962
	Hungary	0.160	0.003	0.006	0.008	—	0.294	—	0.035	0.037	—	0.013	0.005	0.561
	Netherlands	0.166	0.022	0.004	0.008	—	0.022	—	0.068	0.003	—	0.006	0.004	0.303
Urban–home	Belgium	0.383	0.069	0.004	0.004	—	0.059	—	0.001	0.001	—	0.001	0.036	0.557
	Switzerland	0.036	0.001	0.003	0.008	—	0.015	—	0.032	0.125	—	0.004	0.005	0.228
	Slovenia	0.063	0.001	0.004	0.004	—	0.070	—	0.002	0.041	—	0.001	0.005	0.192
	Hungary	0.123	0.006	0.006	0.010	—	0.029	—	0.005	0.034	—	0.007	0.017	0.237
	Netherlands	0.018	0.002	0.001	0.001	—	0.002	—	0.007	0.001	—	0.001	0.011	0.044

NA, not available.

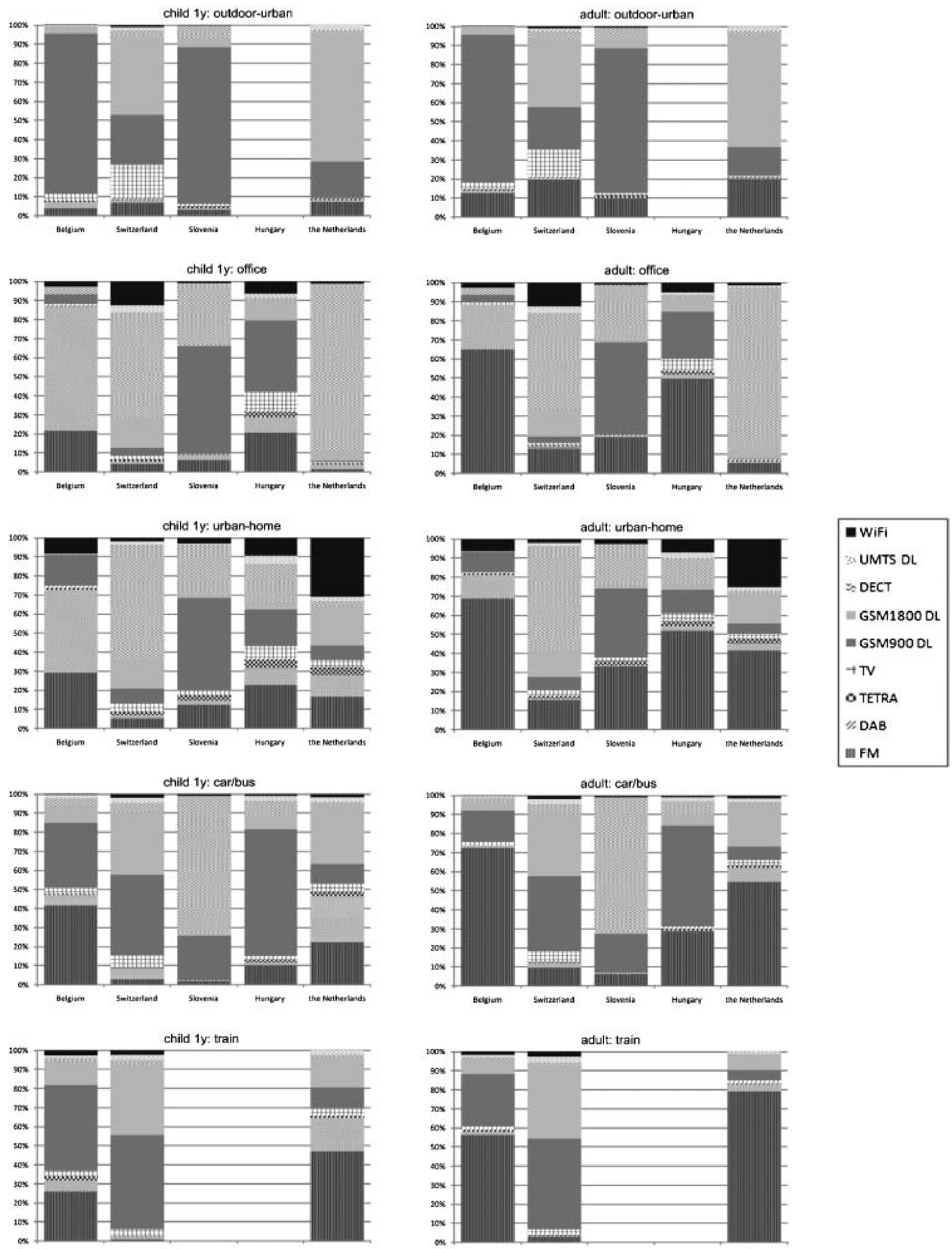

Fig. 5. Comparison of the contribution of the different sources of exposure to SAR_{wb} in child and adult models for all countries (no data are available for trains in Slovania and Hungary and for outdoor–urban in Hungary).

chose to consider the absorption in a 1-year-old child as well to be able to compare absorptions in adults and children in the same setting.

The differences in study design, the selection of study participants in the population surveys, and a limited number of measurements in some microenvironments (e.g., offices in the Netherlands and Belgium) are limitations of the study and are discussed in detail in Joseph et al. [2010b]. Also, due to the effect of shielding of the human body when exposimeters are carried on the body, some measurement values might be underestimated by up to 6.5 dB [Knafl et al., 2008; Iskra et al., 2010, 2011; Joseph et al., 2010b; Bolte et al., 2011].

In the current study, we considered whole-body absorptions from various sources emitting RF-EMF in the frequency range between 80 MHz and 2.5 GHz. However, we did not consider uplink exposure from mobile phones because the SAR calculations require far-field conditions. Uplink exposure from personal mobile phones cause highly localized exposures, which does not fulfill this assumption of far-field conditions and would require a different calculation procedure. For whole-body absorptions, spheroid human body models give a realistic estimation of the SAR_{wb} [Durney et al., 1986] while heterogeneous models would be needed for localized exposure. Uplink from other people's phones would generally fulfill the far-field assumption, and Frei et al. [2010] demonstrated that this contribution is relevant for the average personal exposure. Thus, our SAR_{wb} values somewhat underestimate the total far-field absorption.

We used different propagation models for the different types of microenvironments. Within one microenvironment, the same models were used for all countries (in combination with different measured field values). There are possibly some differences in the microenvironments between countries (probably also within countries) but we do not expect these differences to have a major impact on our analyses, where we were interested in average values and general patterns.

Interpretation

We observed quite consistently in all countries that the highest whole-body absorption contributions were from GSM DL, FM, TV/DAB, and DECT, and mainly for outdoor–urban and office environments (also car/bus in Slovenia). A similar pattern was observed for the power density. This demonstrates that the choice of the exposure surrogate in epidemiology might not be very crucial if interested in the ranking of exposure only. Nevertheless, the relative importance of the TV/DAB contribution is considerably increased in the child phantom compared to the power density; for the adult SAR, the relative importance of FM is increased. The reason for the high values of the SAR_{wb} for TV/DAB in the child phantom at 200 MHz (or lower frequencies such as FM) are because of the dimensions of the 1-year-old child (length of 0.74 m and width of 0.16 m in Durney et al. [1986]). The resonance frequency of the 1-year-old child model is about 200 MHz for a vertically polarized plane wave arriving at a zero elevation angle [Durney et al., 1986], and half the wavelength at 200 MHz is 0.75 m while the length of the 1-year-old child is 0.74 m. Figure 2 explains this too, with higher values for a for FM and TV/DAB for the child than for telecommunication frequencies of 950 MHz or higher. The contribution of FM at 100 MHz is clearly higher in the adult than for the 1-year-old child because FM is closer to the resonance frequency of the adult man than the frequencies of the other signals and sources (73 MHz for the adult according to Durney et al. [1986]).

In some cases, the variations in SAR values between the countries were quite large (Tables 2 and 3). For example, for the TV/DAB band, much lower values occurred in Switzerland in all environments compared to other countries (e.g., Belgium). One reason for this could be that the nationwide coverage of the DAB signal was not yet completed at the time of the measurements in Switzerland. Therefore, mean power densities obtained with the exposimeter and the resulting SAR values were quite low. Absorptions were generally lower in homes, which is a relevant environment in terms of cumulative absorption because one usually spends most of the time at home. Indoor levels are lower due to penetration losses of outdoor sources into homes; this results in lower absorptions compared to outdoors. Also, fewer sources such as WiFi and DECT might be present in homes than in offices. Total power densities in the homes in Joseph et al. [2010b] were quite similar in the different countries and this was also the case for whole-body absorptions, despite the different source contributions in the various countries. The only consistent pattern is that whole-body absorption due to (downlink) mobile telecommunication and FM is important in all countries. However, the exposure contributions in urban homes have to be interpreted with caution. Different recruitment strategies and the limited numbers of participants or microenvironments make a direct comparison difficult.

In trains, the lowest whole-body absorptions occur because uplink exposure was not considered. Several studies demonstrated that uplink is the main exposure source in trains [Frei et al., 2009; Joseph et al., 2010b]. For downlink signals, the metalized windows in trains cause high penetration losses, resulting in low power density values and thus low absorptions. In general, higher absorptions occur in car/bus because of the lower penetration losses compared to trains (no metalized windows), and the fact that buses drive mainly in urban regions while trains have trajectories, which are in less densely populated areas containing fewer base stations. However, the absorptions in cars in Slovenia have to be treated with caution because of the limited number of samples available [Joseph et al., 2010a]. Likewise, for power density values, the whole-body absorptions in all countries are of the same order of magnitude (Table 2) because the same RF-EMF sources and technologies (base stations, FM radio, TV/DAB) are present in similar amounts and densities.

CONCLUSIONS

In this article, a comparison of the whole-body absorption (for child and adult models) based on personal exposure between different countries is made. This enables distinguishing between the field exposure situation and the actual absorption in real circumstances.

Generally, absorption levels were far below the standard limits. It is important to conclude that the higher power densities mostly correspond to higher whole-body absorptions. This implies that field strengths can be considered a valid proxy for absorption when used in epidemiological studies since the ranking between persons is most important in such studies. Nevertheless, exposure to the TV/DAB band caused relatively higher whole-body absorption values for the 1-year-old child (FM for the adult) than signals at higher frequencies due to the body size-dependent absorption rates.

Future research should investigate more environments, such as schools and nurseries, and investigate the effect of different propagation models, distributions, and parameters on the obtained SAR_{wb}. Future developments should also include localized absorptions. Estimations of localized SAR based on exposimeter data is, however, a very challenging task as one will have to distinguish between a participant's own mobile phone exposure and local exposure from the surrounding mobile phones of other people. Nevertheless, the more that appropriate internal exposure can be estimated, the more that reliable exposure comparisons can be made and the more accurate future studies will be, relying on such exposure measures.

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