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ORIGINAL ARTICLE

Radiofrequency electromagnetic field exposure in everyday microenvironments in Europe: A systematic literature review

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The impact of the introduction and advancement in communication technology in recent years on exposure level of the population is largely unknown. The main aim of this study is to systematically review literature on the distribution of radiofrequency electromagnetic field (RF-EMF) exposure in the everyday environment in Europe and summarize key characteristics of various types of RF-EMF studies conducted in the European countries. We systematically searched the ISI Web of Science for relevant literature published between 1 January 2000 and 30 April 2015, which assessed RF-EMF exposure levels by any of the methods: spot measurements, personal measurement with trained researchers and personal measurement with volunteers. Twenty-one published studies met our eligibility criteria of which 10 were spot measurements studies, 5 were personal measurement studies with trained researchers (microenvironmental), 5 were personal measurement studies with volunteers and 1 was a mixed methods study combining data collected by volunteers and trained researchers. RF-EMF data included in the studies were collected between 2005 and 2013. The mean total RF-EMF exposure for spot measurements in European "Homes" and "Outdoor" microenvironments was 0.29 and 0.54 V/m, respectively. In the personal measurements studies with trained researchers, the mean total RF-EMF exposure was 0.24 V/m in "Home" and 0.76 V/m in "Outdoor". In the personal measurement studies with volunteers, the population weighted mean total RF-EMF exposure was 0.16 V/m in "Homes" and 0.20 V/m in "Outdoor". Among all European microenvironments in "Transportation", the highest mean total RF-EMF 1.96 V/m was found in trains of Belgium during 2007 where more than 95% of exposure was contributed by uplink. Typical RF-EMF exposure levels are substantially below regulatory limits. We found considerable differences between studies according to the type of measurements procedures, which precludes cross-country comparison or evaluating temporal trends. A comparable RF-EMF monitoring concept is needed to accurately identify typical RF-EMF exposure levels in the everyday environment.

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INTRODUCTION

With the evolution of communication technology, the number of mobile phone subscribers has increased exponentially and so has the number of mobile phone base stations in the last 15 years. By the end of 2015, the number of mobile phone subscribers reached more than 7 billion globally and this is anticipated to further increase in the future with the introduction of long-term evolution technology.[1] In 2012, the number of small cells and macrocells installed globally was 6 million and 5.9 million, respectively.[2] Typical exposure of the general public to radiofrequency electromagnetic field (RF-EMF) in the everyday microenvironments is difficult to characterize due to the variety in communication technology, the complex nature of RF-EMF exposure quantification and high temporal and spatial variability of RF-EMF in the everyday environments.[3–11]

The increasing number of mobile phone subscriptions and mobile phone base stations has raised public concern for potential health effects caused by RF-EMF exposure below the guideline limits.[12–14] A better knowledge of the typical exposure of the general population to RF-EMF is important to interpret previous epidemiological research, to design better studies in the future, to conduct risk assessment and for risk communication. As a result, the World Health Organization (WHO)[15] declared RF-EMF exposure and the identification of the determinants of the exposure in the general population as a priority in their research agenda.

Different approaches are used to measure RF-EMF exposure.[16] Stationary spot measurements use sophisticated devices for accurately measuring RF-EMF from various sources at a given location. However, most spot measurements are limited in evaluating long-term patterns, as well as spatial coverage. Portable measurement devices are useful to enhance the spatial coverage but often compromise in the selection of the frequency bands and the handling of the meters. Two types of measurement studies with portable devices were conducted: (1) microenvironmental surveys, where a trained researcher collects data in a standardized manner in different accessible public areas such as city centers, homes, workplaces, universities and airports. In this context, a microenvironment is defined as a small area

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distinguished from its immediate surrounding by its function. (2) Volunteer measurements, where a volunteer sample is carrying the devices for 1–7 days while carrying out their everyday normal activities and also recording their activities so that researchers can subsequently assign measurements to a certain microenvironment.

In this study we systematically reviewed the literature focusing on the quantification of the general population`s everyday exposure to RF-EMF (30 MHz to 300 GHz) in different microenvironments in European countries. Our aim was to estimate the typical exposure to RF-EMFs of the population in the 29 European countries (28 EU members plus Switzerland) and to describe the contribution of various sources of exposure in different microenvironments.

MATERIALS AND METHODS

Literature Search Strategy

We systematically searched the ISI Web of Science (http://www.webofknowledge.com) for relevant literature published between 1 January 2000 and 30 April 2015. The search terms were derived from four search categories denoting “exposure characteristics”, “study subject/area”, “exposure assessment/measurement” and “radiation source” (Supplementary Material: Supplementary Table S1).

Inclusion and Exclusion Criteria

We included original research articles published in English or in German as a full publication in a peer-reviewed journal. We considered only articles on RF-EMF exposure assessment conducted in the 29 European countries. We included spot measurements studies, personal measurement studies with trained researchers (microenvironmental) and personal measurement studies with volunteers using portable devices (exposimeters) alone or a mixture of all and/or any two types. The eligible studies had to report mean RF-EMF exposure levels (or enough data to allow calculation) in at least one specified microenvironment. In case of duplicate publications, we included the article with the most comprehensive data.

We excluded the articles that were based on data outside the 29 European countries or studies reporting occupational measurements. Reviews, comments, purely methodological papers and editorials were not considered either in this review. Studies that applied a non-representative sampling strategy (i.e. only looking for “highest value” areas or micro-modeling around a few meters of base stations) did not meet the inclusion criteria. Some articles reported modeled exposure only and were thus excluded.

Data Extraction

The literature search results were screened by two independent reviewers and any discrepancies raised were resolved by discussion. We extracted the relevant data from each eligible study by using a structured extraction sheet, prepared and approved by all reviewers’ consensus after screening

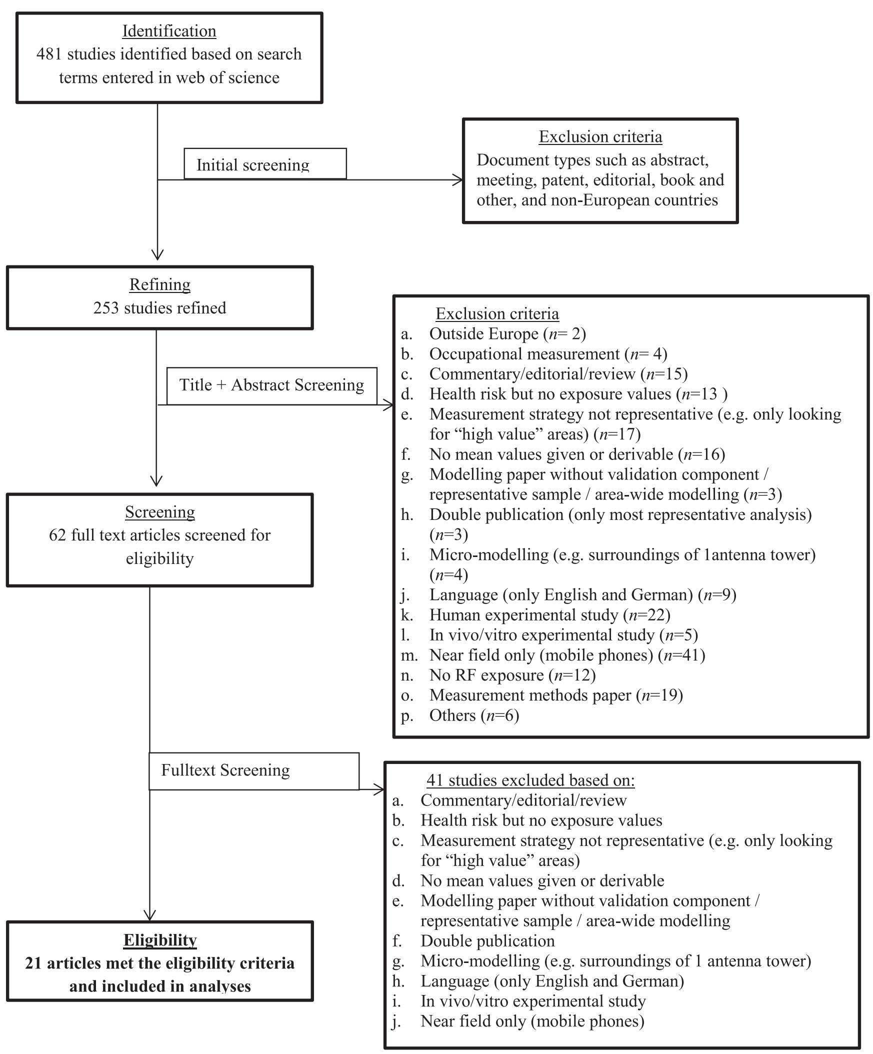

Figure 1. Flowchart showing the identification and selection of studies on radiofrequency electromagnetic field (RF-EMF) in European countries.

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Table 1. Overview of 21 eligible studies.

			Type of measurement			Data collection
Country	*Study*	*ID*	*Spot measurement*	*Personal with trained reseracher (microenvironmental)*	*Personal measurement with volunteer*	*Date*
Austria	Tomitsch and Dechant[23]	8	✓			2006–2012
Belgium	Aerts et al.[21]	1	✓			March–August 2012
	Joseph et al.[6]	21		✓		2007
	Joseph et al.[18,a]	6	✓			September 2009–April 2010
	Urbinello et al.[9,a]	23		✓		November 2010–March 2012
	Urbinello et al.[10,a]	24		✓		April 2011–March 2012
	Verloock et al.[24]	9	✓			November 2009
	Vermeeren et al.[19,a]	10	✓			2013
France	Viel et al.[33]	35			✓	December 2005–September 2006
Germany	Breckenkamp et al.[27]	4	✓			March–August 2006
	Thomas et al.[31]	33			✓	January 2005–August 2006
	Thomas et al.[32]	34			✓	February 2006–August 2012
Greece	Vermeeren et al.[19,a]	10	✓			2013
Hungary	Joseph et al.[17,a]	32			✓	2007–2009
Netherlands	Beekhuizen et al.[25]	3	✓			2008
	Bolte and Eikelboom[30]	30			✓	2009
	Joseph et al.[17,a]	32		✓		2007–2009
	Joseph et al., [18,a]	6	✓			September 2009–April 2010
	Urbinello et al.[9,a]	23		✓		November 2010–March, 2012
	Beekhuizen et al.[26]	2	✓			Not mentioned
Slovenia	Joseph et al.[17,a]	32			✓	2007–2009
Sweden	Estenberg and Augustsson,[29]	20		✓		2012
	Joseph et al.[18,a]	6	✓			September 2009–April 2010
Switzerland	Bürgi et al.[20]	5	✓			March–April 2005
	Frei et al.[4]	31			✓	April 2007–Februray 2008
	Urbinello et al.[9,a]	23		✓		November 2010–March 2012
	Urbinello et al.[11,a]	24		✓		April 2011–March 2012
	Urbinello and Röösli[28]	25		✓		January 2010–January 2011
United Kingdom	Joseph et al.[22]	7	✓			Februray 2011

[a]Multinational studies.

of the eligible studies. The approved extraction sheet had two components: one component included study characteristics such as type of measurements, frequency bands used, country of measurement, types of microenvironments (outdoor, indoor, shopping centers, bedroom and others) measurement, devices used, year of data collection, sampling method used and any inclusion/exclusion criteria. The second component included measurement results of each eligible study such as mean and variability values reported, detection limit reported or ignored and individual frequency bands grouped into downlink (exposure from a base station to a mobile phone handset), uplink (exposure from a mobile phone handset to a base station), broadcasting (exposure from FM and TV antennas) and total RF-EMF (downlink, uplink and broadcasting combined). All eligible papers were distributed to seven primary reviewers to extract data for both components of the extraction sheet. In case where primary reviewers failed to extract the data or felt unsure about which data to extract, the article was passed on to one of the two secondary reviewers who conducted an in-depth extraction, and any disagreements or uncertainties were then resolved by discussion among the reviewers.

Data Analysis

The data were mostly descriptively analyzed according to the type of study and the type of microenvironment. For personal measurement studies with volunteers, we also calculated study population weighted mean values for each microenvironment by giving each study a weight proportional to the number of volunteers. All analyses were done by MS Excel and statistical software R version 3.1.3 (https://www.rproject.org/).

RESULTS

Selection of Studies

The database search yielded 481 studies with the search terms used. After excluding certain document types (abstract, meeting, patent, editorial and book) and non-European countries, 253 papers remained. After screening of the abstracts, 191 papers were excluded based on our inclusion and exclusion criteria. Sixty-two full-text articles were screened for eligibility and 41 were subsequently excluded. Eventually, 21 studies met the eligibility criteria and were included in the further analyses (Figure 1).

Characteristics of Exposure Assessment and Monitoring in the European Countries

Out of 21 eligible studies, we found 10 spot measurement studies, 5 personal measurement studies with trained researchers (microenvironmental), 5 personal measurement studies with volunteers and 1 mixed method (ID 22 and ID 32) study[17] combining data collected by volunteers and trained researchers (Table 1). We found that 11 out of 29 selected European countries have conducted at least one RF-EMF exposure assessment since 2000, 1 multi-country study from Austria, France, Greece, Hungary, Slovenia and the United Kingdom, 2 studies from Sweden, 3 studies from Germany, 5 studies from Switzerland, 6 studies from the Netherlands and 7 studies from Belgium. Five[9,11,17–19] out of 21 eligible studies were multinational studies that included either

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Table 2. Sampling method used by each of the eligible studies.

Authors	Country	ID	Type of study	Devices used	Sample selection method	
					Random sampling	*Representative, not random*
Aerts et al.[21]	Belgium	1	Spot measurement	NBM-550 broadband field meter with an EF-0391 isotropic electric field probe		✓
Beekhuizen et al.[26]	The Netherlands	2		EME SPY 140		✓
Beekhuizen et al.[25]	The Netherlands	3		EME SPY 140		✓
Breckenkamp et al.[27]	Germany	4		EME SPY 120		✓
Bürgi et al.[20]	Switzerland	5		NARDA SRM-3000		✓
Joseph et al.[18]	Belgium, The Netherlands and Sweden	6		Spectrum analyzer of type R&S FSL6, consisted of triaxial Rohde and Schwarz R&S TS-EMF Isotropic antennas	✓	
Joseph et al.[22]	United Kingdom	7		Tri-axial Rohde and Schwarz TS-EMF isotropic antennas	✓	
Tomitsch and Dechant[23]	Austria	8		Spectrum analyser (MT8220A, Anritsu, Morgan Hill, CA) and two biconical antennas (SBA 9113 and BBVU9135þUBAA9114, Schwarzbeck, Schönau, Germany)	✓	
Verloock et al.[24]	Belgium	9		Spectral analyzer and isotropic antenna (Narda NBM-550)		✓
Vermeeren et al.[19]	Belgium and Greece	10		EME SPY 140 and EME SPY 121		✓
Estenberg and Augustsson[29]	Sweden	20	Personal measurement with trained researcher	A spectrum analyzer (FSL 6; Rohde and Schwarz, Munich, Germany) and a three-axis measuring antenna (Satimo 30 MHz–3 GHz; Rohde and Schwarz)		✓
Joseph et al.[6]	Belgium	21		DSP120 EMESPY		✓
Joseph et al.[17]	The Netherlands	22		EME SPY 120, EME SPY 121		✓
Urbinello et al.[9]	Belgium (Brussels) Belgium (Ghent) Switzerland (Basel first measurement) Switzerland (Basel second measurement) The Netherlands (Amsterdam)	23		EME SPY 120		✓
Urbinello et al.[11]	Belgium (Brussels) Belgium (Ghent) Switzerland (Basel)	24		EME SPY 120		✓
Urbinello and Röösli[28]	Switzerland	25		EME SPY 120		✓
Bolte and Eikelboom[30]	The Netherlands	30	Personal measurement with volunteers	EME SPY 121		✓
Frei et al.[4]	Switzerland	31		EME SPY 120		✓
Joseph et al.[17]	Hungary Slovenia Switzerland	32		EME SPY 120 and EME SPY 121		✓
Thomas et al.[31]	Germany	33		ESM 140	✓	
Thomas et al.[32]	Germany	34		ESM 140	✓	
Viel et al.[33]	France	35		EME SPY 120	✓	

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spot measurements, personal measurement studies with trained researchers or personal measurement studies with volunteers for the exposure assessment. Of the 21 eligible studies, the oldest RF-EMF exposure data comes from a spot measurement study conducted in Switzerland during March and April 2005 ([ref. 20]) and the most recent data was collected in Belgium and Greece[19] in 2013 (Table 1).

Table 2 summarizes the sample selection method used by each of the reviewed studies. We found spot measurement studies used either random sampling or representative sampling for micro-environment selection. All of the personal measurement studies with trained researchers used representative but not random selection criteria for microenvironments selection. All of the personal measurement studies with volunteer studies used either random or convenient sampling techniques for volunteer selection.

Characteristics of the Eligible Study Types

Spot measurements. Out of the 21 eligible studies, 10 studies included spot measurements that measured RF-EMF using various RF-EMF measuring devices. Six of the spot measurement studies were conducted using Spectrum analyzer and isotropic antenna[20–24] and four studies were conducted using different versions of EME Spy device.[19,25–27] Five studies reported data from outdoor microenvironments,[20–22,25,26] five studies reported data from indoor microenvironments[18,19,23,24,27] and one study reported mixed data comprising both outdoor and indoor microenvironments.[26] The detail of the devices with their trade names and microenvironments that were used for exposure measurements have been listed under Supplementary Material (Supplementary Table S2).

Personal measurements with trained researchers. Five eligible personal measurement studies with trained researchers reported RF-EMF exposure data using two different types of measuring devices; four studies[6,9,11,28] used EME Spy 120 device (mixed study ID 22 used EME Spy 121 in addition) and one study[29] used a spectrum analyzer (FSL 6; Rohde and Schwarz, Munich, Germany) and a three-axis measuring antenna (Satimo 30 MHz–3 GHz; Rohde and Schwarz). From the five eligible studies, two studies[9,29] reported RF-EMF exposure data from outdoor micro-environments only, one study[11] reported data from indoor microenvironments only and two studies[6,17] reported mixed data from indoor and outdoor microenvironments separately. In terms of exposure in public transportation, four of the studies[6,11,17,28] reported exposure data from different means of public transportation (Supplementary Material: Supplementary Table S3).

Personal measurements with volunteers. Five out of 21 eligible studies were reported using personal measurement with volunteers[4,30–33] with 1 mixed method (ID 32).[17] Three of the five personal measurement studies with volunteers assessed RF-EMF exposure using different versions of EME Spy device.[4,30,33] Two of the studies[31,32] used ESM 140 and the mixed method study[17] used EME Spy 120 and EME Spy 121. Two of the reported personal measurement studies with volunteer[4,33] used the EME Spy 120 device and one study[30] used the EME Spy 121 device. Three[4,17,30] of the six personal measurement studies reported data from outdoor microenvironment, indoor microenvironments and public transportation separately. The remaining three studies[31–33] reported data from different microenvironments and public transportation unspecified where means of public transportation such as bus, tram, and train were not specified (Supplementary Material: Supplementary Table S4).

Summary of RF-EMF Exposure Situation

Table 3 summarizes the data extracted from the 10 eligible spot measurement studies conducted in different microenvironments of 8 European countries. Nine of the 10 eligible spot measurements studies reported mean RF-EMF exposure values except Joseph et al.,[18] where median was reported. Table 4 summarizes the mean RF-EMF exposure of the six eligible personal measurement studies conducted by trained researchers in different microenvironments including public transportation from four European countries. Table 5 summarizes the mean RF-EMF exposure of the six eligible personal measurement studies conducted by volunteers using portable devices (exposimeters) in different microenvironments including means of transportation from six European countries. Three[4,30,33] out of these five studies with volunteers provided mean personal exposure across the study sample from which we calculated a study volunteers weighted average RF-EMF exposure of 0.21 V/m. Highest personal exposure was 0.66 V/m for 1 week.[4]

Home. Figure 2 displays the mean RF-EMF exposure at European "Homes" from 21 eligible studies. Three out of the 10 spot measurements studies, 1 out of the 5 personal measurement studies with trained researchers and 4 out of the 5 personal measurements studies with volunteers and 1 mixed method study (ID 32)[17] reported average RF-EMF values at "Homes". Mean exposure levels ranged from 0.12 V/m in a German volunteer study to 0.37 V/m in an Austrian spot measurement study with volunteers. The average value over all spot measurement studies at "Homes" was 0.29 V/m (Figure 2a Spot Measurement). Downlink and DECT contributed the most to the total RF-EMF in "Homes" in these studies: 45% downlink and 38% DECT in the 219 bedrooms in Austrian homes, and 14% downlink, and 48% DECT in 15 homes in Belgium and Greece. WLAN contributed about 10% in Austrian homes and 6% in Belgium and Greece. Broadcasting contributed $<10\%$ of the total RF-EMF exposure in the homes of both Austria, and Belgium and Greece. This proportion was, however, larger than in studies with exposimeters. Less variability was observed in the volunteer studies ranging from 0.18 (Hungary) to 0.24 V/m (The Netherlands) with the exception of France, where only 0.10 V/m was measured (Figure 2c Personal Measurement with Volunteers). The weighted mean exposure across these studies was 0.16 V/m. Weighted mean RF-EMF from downlink, uplink and DECT was 0.08 V/m, and for WLAN and broadcasting was 0.05 V/m. As volunteers are not forced to turn off their mobile phones, uplink is also relevant in these measurements and contributed between 21% and 44%. The temporal trend of the mean total RF-EMF exposure distribution in the personal measurement studies with volunteers showed an increasing tendency since 2005/06. The only available "Home" measurements conducted with trained researcher studies yielded a mean exposure of 0.24 V/m in 19 "Homes" in the Netherlands with 92% of this exposure originating from uplink (Figure 2b Personal Measurement with Trained Researchers).

Outdoor microenvironment. Figure 3 displays the mean RF-EMF at European "Outdoor" environments from the 21 eligible studies. Five out of the 10 spot measurements studies, 4 out of the 5 personal measurement studies with trained researchers and all of the 5 personal measurements studies with volunteers and 1 mixed method study [17] reported average RF-EMF values at "Outdoor" microenvironments. There was a large variability in exposure ranging from 0.11 V/m (France)[33] to 1.59 V/m (Sweden).[29] The average value over all studies was 0.63 V/m with somewhat higher values for personal measurement studies with trained researchers (0.76 V/m) compared with spot measurement studies (0.54 V/m) and personal volunteer studies (0.32 V/m). The weighted mean exposure across personal measurement studies with volunteers at

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Table 3. Mean EMF exposure in spot measurements studies (all values are in V/m EXCEPT number of spots/areas).

Authors	*Country*	*ID*	*Microenvironments*	*No. of spots/areas*	*Total RF-EMF*	*Downlink*	*Uplink*	*DECT*	*WLAN*	*Broadcasting*	*Unspecified*	*Maximum*	*Year of survey*
Aerts et al.[21]	Belgium	1	Urban outdoor	1	0.49	0.49	Not applicable	Not reported	Not reported	Not reported		1.18	March–August 2012
Beekhuizen et al.[26]	The Netherlands	2	Indoor unspecified	131	0.12	0.12	Not applicable	Not reported	Not reported	Not reported		0.73	2003/2004
Beekhuizen et al.[25]	The Netherlands	3	Urban outdoor	5	0.29	0.29	Not applicable	Not reported	Not reported	Not reported		0.39	2008
Breckenkamp et al.[27]	Germany	4	Bedroom	1348	0.12	0.03	Not applicable	0.09	0.05	0.03		1.15	March–August 2006
Bürgi et al.[20]	Switzerland	5	Urban outdoor (Basel City)	20	0.50	0.45	Not applicable	Not reported	Not reported	0.04	0.22	1.5	March–April 2005
			Urban outdoor (Bubendorf City)	18	0.15	0.11	Not applicable	Not reported	Not reported	0.05	0.09		
Joseph et al.[18]	Belgium, The Netherlands and Sweden	6	Indoor, unspecified[a]	68	0.28	0.11	Not applicable	0.12	0.04	0.07		3.9	September 2009–April 2010
			Outdoor unspecified[a]	243	0.51	0.4	Not applicable	0.06	0.01	0.08			
Joseph et al.[22]	United Kingdom	7	Urban outdoor	40	0.93	0.56	Not applicable	Not reported	Not reported	0.6	0.44	4.46	February 2011
Tomitsch and Dechant,[23]	Austria	8	Bedroom, only	219	0.37	0.25	Not applicable	0.23	0.12	0.10		Not reported	2006–2012
Verloock et al.[24]	Belgium	9	Office (workplace)	1	0.12	Not reported	Not applicable	Not reported	0.12	Not reported		2.9	November 2009
Vermeeren et al.[19]	Belgium and Greece	10	Schools (workplace)	24	0.4	0.24	Not applicable	0.07	0.07	0.2	0.23	2.1	2013
			Homes	15	0.33	0.14	Not applicable	0.26	0.09	0.11	0.18		
			Offices	9	0.93	0.43	Not applicable	0.11	0.11	0.82			

[a]Median values in V/m.

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Table 4. Mean EMF exposure in personal measurement with trained researchers studies ((all values are in V/m except number of areas).

Personal measurement study with trained researchers (microenvironmental)

Authors	*Country*	*ID*	*Microenvironments*	*No. of area*	*Total RF-EMF*	*Downlink*	*Uplink*	*DECT*	*WLAN*	*Broadcasting*	*Unspecified*	*Maximum*	*Year of survey*
Estenberg and Augustsson,[29]	Sweden	20	Ryssby, Ekerö (rural outdoor)	2	0.29	0.27	0.01	0.00	0.00	0.06	0.09	Not reported	2012
			Göteborg, Helsingborg, Jönköping, Ljungby (urban outdoor)	4	0.75	0.67	0.02	0.01	0.02	0.17	0.30		
			Stockholm (urban outdoor)	1	1.59	1.43	0.02	0.01	0.01	0.16	0.70		
			Solna (urban outdoor)	1	1.10	0.97	0.01	0.00	0.00	0.09	0.52		
Joseph et al.[6]	Belgium	21	Urban indoor	9	1.10	0.28	0.23	0.37	0.73	0.70			2007
			Urban outdoor	4	0.92	0.82	0.10	0.13	< 0.1	0.39			
			Rural outdoor	2	0.22	0.21	0.07	0.07	< 0.07	< 0.07			
			Rural indoor	2	< 0.07	< 0.07	< 0.07	< 0.07	< 0.07	< 0.07			
			Train	1	0.93	0.10	0.93	< 0.05	< 0.05	< 0.05		1.96	
			Train	1	1.96	0.19	1.95	< 0.05	< 0.05	0.12			
			Bus	1	0.63	0.29	0.45	< 0.05	< 0.05	0.32			
			Car	2	0.34	0.31	< 0.07	< 0.07	< 0.07	0.09			
			Cycling	1	0.27	0.23	< 0.05	< 0.05	< 0.05	0.13			
Joseph et al.[17]	The Netherlands	22	Urban Outdoor	51	0.42	0.36	0.19	0.06	0.00	0.10			2007–2009
			Office (workplace)	3	0.91	0.04	0.89	0.15	0.02	0.03		3.9	
			Home unspecified	19	0.23	0.04	0.23	0.00	0.04	0.03			
			Trains	11	0.53	0.08	0.52	0.02	0.00	0.09			
			Car/bus	19	0.64	0.12	0.62	0.02	0.03	0.09			
Urbinello et al.[9]	Belgium	23	Urban residential (Brusels +Ghent)	4	0.64	0.50	0.28	Not reported	Not reported	Not reported			November 2010–March 2012
			Downtown (Brusels +Ghent)	2	0.66	0.58	0.23	Not reported	Not reported	Not reported			
	Switzerland		Urban residential (Basel)	2	0.43	0.36	0.20	Not reported	Not reported	Not reported		Not reported	
			Downtown (Basel)	2	0.60	0.56	0.17	Not reported	Not reported	Not reported			
	The Netherlands		Urban residential (Amsterdam)	2	0.54	0.48	0.20	Not reported	Not reported	Not reported			
			Downtown (Amsterdam)	1	0.57	0.51	0.17	Not reported	Not reported	Not reported			
Urbinello et al.[11]	Belgium (Brussels + Ghent)	24	Indoor shopping mall	2	0.49	0.30	0.31	Not reported	Not reported	Not reported			April 2011–March 2012
			Airport	1	0.53	0.50	0.17	Not reported	Not reported	Not reported			
			Railway station	2	0.65	0.55	0.31	Not reported	Not reported	Not reported			
			Public transport unspecified	2	1.11	0.19	1.09	Not reported	Not reported	Not reported			
			Trains	2	1.35	0.09	1.34	Not reported	Not reported	Not reported			
			Bus/minibus	2	0.52	0.25	0.43	Not reported	Not reported	Not reported			
			Metro	1	0.70	0.16	0.67	Not reported	Not reported	Not reported			

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Table 4. (Continued)

Authors	Country	ID	Microenvironments	No. of area	Total RF-EMF	Downlink	Uplink	DECT	WLAN	Broadcasting	Unspecified	Maximum	Year of survey
Personal measurement study with trained researchers (microenvironmental)													
			Tram	1	0.50	0.27	0.41	Not reported	Not reported	not reported			
	Switzerland (Basel)		Indoor shopping mall	1	0.22	0.12	0.15	Not reported	Not reported	Not reported			
			Airport	1	0.54	0.51	0.15	Not reported	Not reported	Not reported			
			Railway station	1	0.34	0.22	0.23	Not reported	Not reported	Not reported			
			Public transport unspecified	1	0.59	0.19	0.55	Not reported	Not reported	Not reported			
			Trains	1	0.97	0.09	0.96	Not reported	Not reported	Not reported		1.29	
			Tram	1	0.32	0.23	0.21	Not reported	Not reported	Not reported			
			Bus/minibus	1	0.35	0.21	0.27	Not reported	Not reported	Not reported			
Urbinello and Röösli[28]	Switzerland	25	Railway station	NA	0.16	NA	0.16	Not reported	Not reported	Not reported		Not reported	January 2010–January 2011
			Trains	NA	0.48	NA	0.48	Not reported	Not reported	Not reported			
			Bus/minibus	NA	0.15	NA	0.15	Not reported	Not reported	Not reported			
			Car/van/truck	NA	0.04	NA	0.04	Not reported	Not reported	Not reported			

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Table 5. Mean EMF exposure in personal measurements with volunteer studies (all values are in V/m except number of volunteers).

Personal measurement study with volunteers

Authors	*Country*	*ID*	*Microenvironments*	*No. of volunteers*	*Total RF-EMF*	*Downlink*	*Uplink*	*DECT*	*WLAN*	*Broadcasting*	*Unspecified*	*Maximum*	*Year of survey*
Bolte and Eikelboom[30]	The Netherlands	30	Outdoor, unspecified	98	0.28	0.17	0.20	0.06	0.02	0.08			2009
			Indoor, unspecified		0.25	0.14	0.19	0.04	0.02	0.05			
			Home unspecified (including bedroom)		0.24	0.08	0.11	0.16	0.11	0.05			
			Bedroom only		0.20	0.09	0.10	0.08	0.1	0.06			
			Office (workplace)		0.28	0.09	0.22	0.13	0.05	0.05			
			Workplace, unspecified (not restricted to office only)		0.27	0.09	0.22	0.03	0.04	0.10			
			Indoor shopping mall		0.25	0.09	0.21	0.1	0.03	0.03		0.54	
			Railway station		0.35	0.31	0.07	Not reported	0.04	0.14			
			Trains		0.37	0.09	0.35	0.02	0.00	0.04			
			Tram/metro		0.34	0.20	0.25	0.02	0.03	0.10			
			Bus/minibus		0.29	0.15	0.24	0.00	0.00	0.05			
			Car/van/truck		0.54	0.12	0.51	0.05	0.07	0.08			
			Bicycle		0.27	0.19	0.15	0.03	0.02	0.11			
Frei et al.[9]	Switzerland	31	Home	129	0.19	0.13	0.09	0.11	Not reported	Not reported		0.66	April 2007–Februray 2008
			Workplace		0.26	0.20	0.12	0.12	Not reported	Not reported			
			Outdoor		0.28	0.21	0.16	Not reported	Not reported	Not reported	0.1		
			Friends place, leisure residence		0.17	Not reported	0.11	0.09	Not reported	Not reported	0.10		
			Car		0.29	Not reported	0.25	Not reported	Not reported	Not reported	0.15		
			Resturant, bar		0.25	Not reported	0.20	Not reported	Not reported	Not reported	0.15		
			Shopping		0.29	Not reported	0.22	Not reported	Not reported	Not reported	0.19		
			Sports halls		0.18	Not reported	0.15	Not reported	Not reported		0.10		
			Tramway, bus		0.37	Not reported	0.31	Not reported	Not reported	Not reported	0.21		
			Train		0.66	Not reported	0.64	Not reported	Not reported	Not reported	0.17		
			Cinema		0.15	Not reported	0.14	Not reported	Not reported	Not reported	0.06		
			University		0.2	Not reported	0.17	Not reported	Not reported	Not reported	0.11		
			Hospital		0.25	Not reported	0.20	Not reported	Not reported	Not reported	0.15		
			School building		0.09	0.06	Not reported	Not reported	Not reported	Not reported	0.07		
			Church		0.17	0.14	Not reported	Not reported	Not reported	Not reported	0.10		
			Airport		0.53	Not reported	0.51	Not reported	Not reported	Not reported	0.11		

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Table 5. (Continued)

Authors	Country	ID	Microenvironments	No. of volunteers	Total RF-EMF	Downlink	Uplink	DECT	WLAN	Broadcasting	Unspecified	Maximum	Year of survey
Personal measurement study with volunteers													
			Average exposure at different location from different sources		0.22	Not reported	Not reported	Not reported	Not reported	Not reported			
Joseph et al.[6]	Hungary	32	Urban outdoor	138	Not reported	Not reported	Not reported	Not reported	Not reported	Not reported			2007–2009
			Office (workplace)		0.22	0.10	0.17	0.02	0.04	0.07			
			Home unspecified		0.18	0.07	0.12	0.07	0.05	0.07			
			Trains		Not reported	Not reported	Not reported	Not reported	Not reported	Not reported		Not reported	
			Car/bus		0.39	0.21	0.30	0.07	0.03	0.08			
	Slovenia		Urban Outdoor	20	0.46	0.22	0.40	0.06	0.02	0.05			
			Office (workplace)		0.37	0.18	0.28	0.15	0.03	0.06			
			Home unspecified		0.20	0.10	0.14	0.08	0.03	0.05			
			Trains		Not reported	Not reported	Not reported	Not reported	Not reported	Not reported			
			Car/bus		0.75	0.17	0.66	0.31	0.03	0.05			
Thomas et al.[31]	Germany	33	All areas (waking hours), adults	329	0.07	Not reported	Not reported	Not reported	0.04	Not reported		0.29	January 2005–August 2006
Thomas et al.[32]	Germany	34	All areas (waking hours), children and adolescents	3022	0.09	Not reported	Not reported	Not reported	Not reported	Not reported		0.46	February 2006–December 2007
Viel et al.[33]	France	35	Home	377	0.10	0.05	0.05	0.04	0.04	0.05		Not reported	December 2005–September 2006
			Workplace		0.09	0.05	0.03	0.03	0.04	0.05			
			Urban		0.11	0.05	0.05	0.04	0.05	0.07			
			Periurban		0.09	0.05	0.04	0.04	0.04	0.04			
			Rural		0.08	0.05	0.03	0.03	0.04	0.02			
			Transportation		0.10	0.05	0.05	0.03	0.04	0.05			

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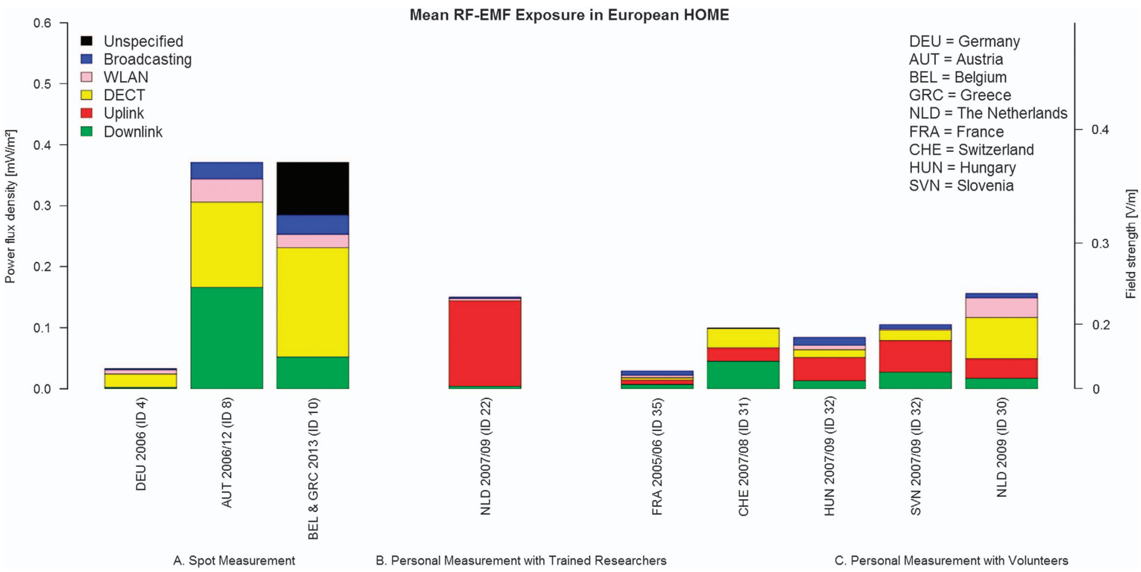

Figure 2. Mean radiofrequency electromagnetic field (RF-EMF) levels at "Home" across type of study (arranged chronically by spot measurement, personal measurement with trained researchers and personal measurement with volunteers).

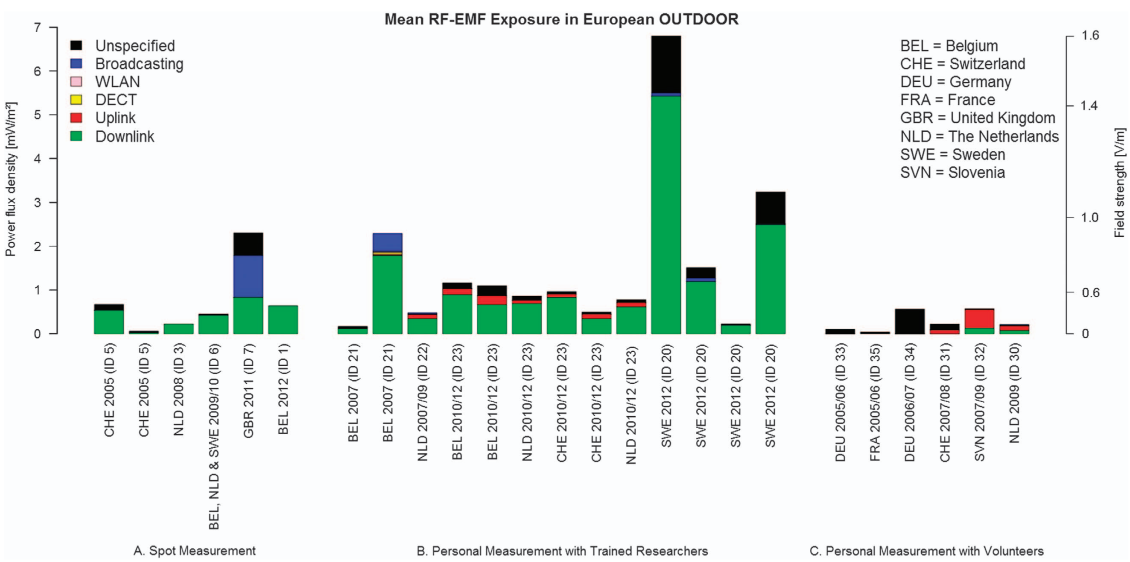

Figure 3. Mean radiofrequency electromagnetic field (RF-EMF) levels at "Outdoor" locations for different type of studies (arranged chronically by spot measurement, personal measurement with trained researchers and personal measurement with volunteers).

outdoor microenvironments was 0.20 V/m. Weighted mean RF-EMF from downlink was 0.09 V/m, uplink was 0.13 V/m, DECT and WLAN was 0.04 V/m, and for WLAN and broadcasting was 0.07 V/m.

Downlink contributed the most to the total RF-EMF in "Outdoor" microenvironments in all measurement study with trained researchers and all spot measurement studies, except urban outdoor environment in Reading, UK.[22] Typically, downlink contribution to mean total RF-EMF was around 80% in these studies. In personal measurement, studies with volunteers contribution of downlink to total RF-EMF was lower. In Slovenia, downlink contributed 22% and uplink contributed 76% to the mean total RF-EMF exposure. In Swiss outdoor microenvironments, downlink contributed 53%. In the Dutch outdoor microenvironments, downlink contributed 37% and uplink contributed 51% to the mean total RF-EMF (Figure 3c Personal Measurement with Volunteers).

Public transport. Figure 4 displays the mean RF-EMF exposure in the various means of transportation by study types: personal measurement studies with trained researchers and personal measurement studies with volunteers. For a comparison across the means of transportation, we categorized them into public and private transportation. Variability of RF-EMF exposure was very high but it is obvious that in public transportation uplink is by far the most relevant contributor. The exposure ranged between 0.004 V/m in car/van/truck (Switzerland)[28] to 1.96 V/m in train (Belgium).[6] The average over all studies was 0.69 V/m with somewhat higher values for personal measurement studies with trained researchers (0.79 V/m) compared with 0.43 V/m across personal measurement studies with volunteers.

Uplink contributed the most to the total RF-EMF in different "Transportation" in all personal measurement studies, except during cycling,[6,30] and in a car measurement conducted by a trained researcher.[6] Typically, uplink contribution to mean total

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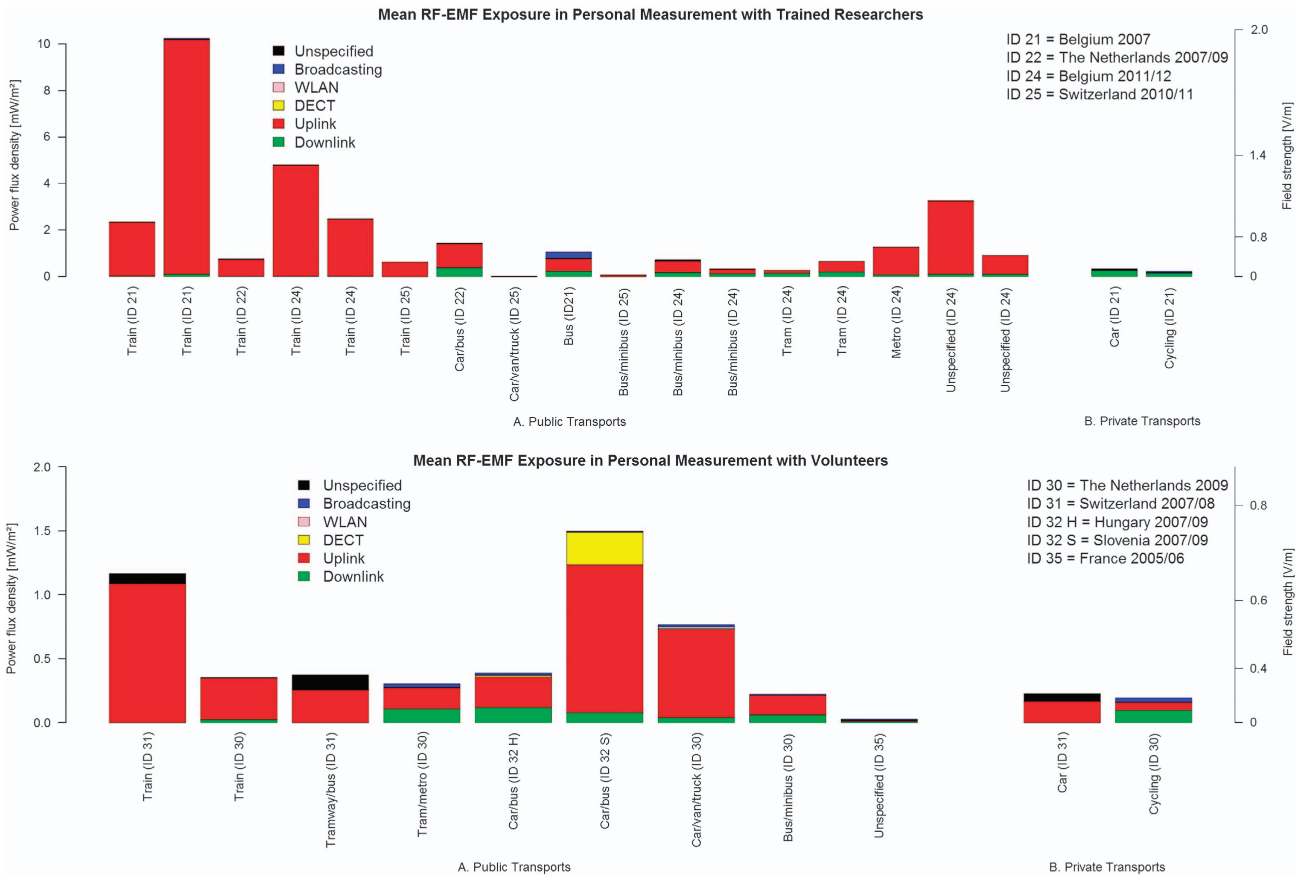

Figure 4. Mean radiofrequency electromagnetic field (RF-EMF) levels in public transportation across type of study (arranged chronically by personal measurement with trained researchers and personal measurement with volunteers).

RF-EMF was around 85% in public transportation. Downlink contributed the most in car[6] and cycling[6] in Belgium, which could be expected, as such types of transportation are mainly used in the main part of city where downlink exposures are significant.

DISCUSSION

This systematic review reveals that comparing exposure measurements from different type of studies is challenging and includes a lot of uncertainty. Nevertheless, some overall exposure patterns can be derived to characterize the typical levels and contribution of different sources to the total RF-EMF exposure in various European microenvironments including different modes of public transportation.

Although we applied a very broad search strategy and various type of RF-EMF exposure assessment methods, there are not many published studies on RF-EMF exposure assessment in different microenvironments in European countries that met our inclusion criteria. Specifically, we included studies that followed a representative sampling strategy not specifically focusing on high exposure environments. We thus excluded studies that stated, for example, to focus on schools or homes close to mobile phone base stations. With this strategy only 21 studies remained for summarizing the typical exposure situations.

The assessment of the representativeness of the sampling strategy applied in each study was, however, a particular challenge for this review. For example, we excluded spot measurement studies such as Verloock et al.,[34] where it was stated that school and homes for measurements were selected in the vicinity of several broadcast transmitters and/or telecommunication base stations. They reported a mean total RF-EMF value of 1.0 V/m in16 offices in Belgium measured between October 2012 and April 2013. However, without context information it is difficult to estimate how representative their measurements are for the office situation in general. On the other hand, selecting measurement sites truly representative for population exposure, is challenging and no standard procedure has been established so far. Thus, we cannot exclude that some of the studies reporting higher levels have focused *a priori* on areas with enhanced exposure levels. In general, it is well conceivable that the results from spot measurements and personal measurement studies with trained researcher are rather an overestimation than underestimation of the typical exposure, as researchers may have tended to focus on the areas with prior known for higher exposure.

Another important challenge for comparing the typical RF-EMF exposure values was the different kinds of devices used for exposure measurement across the 21 eligible studies included in the review. Although typically calibrated for the center frequency of each band they may still behave differently at the border of each frequency band and for different pulsation duration. Also different measurement settings may be chosen such as the "maximum-hold mode" with the root-mean-square detector, that is, maximum values are retained for each component for different time intervals. As an example Joseph et al.,[22] reported mean total RF-EMF of 0.93 V/m from 40 locations in an urban outdoor in Reading, UK using a maximum hold setting of 5 s to 1 min until the signal was stabilized.[22] In this case, the exposure value is likely to be somewhat overestimated compared to a mean exposure

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measurement. Furthermore, outdoor exposure levels are indeed highest for this study compared with all other spot measurement studies. For downlink measurements, one study extrapolated the measurements to maximum transmission load,[23] which may explain the higher downlink levels in homes compared to a German study conducted in 2006 as well.[27] We must also consider that not all devices measure exactly the same frequency bands. Most spectrum analyzers include more frequency bands characterizing broadcasting compared to the exposimeters and this may explain why the contribution of broadcasting is somewhat higher in the spot measurement studies than in the other types of studies (Figure 3). Obviously, this also affects the calculation of total RF-EMF exposure from all measured frequency bands. This issue has been further supported by a recent study, Bolte,[35] which sheds light on possible biases and uncertainties in measurement surveys of RF-EMF with exposimeters. In principle such biases and uncertainties, namely mechanical errors, design of hardware and software filters, anisotropy and influence of the body can be corrected by determining multiplicative correction factors.[35] However, the derivation of such factors would need long measurement series, as such factors are expected to be device specific and depend on the effective frequency distribution within each band.

There are also other systematic differences according to type of studies. Spot measurement studies and personal measurement studies with trained researchers were mostly conducted during the day when RF-EMF sources emit the most, except the study by Berg-Beckhoff et al.,[36] which found much lower levels. In principle, one could also conduct spot measurements during night to compare the two exposure situations. There is scarce information on RF-EMF night time exposure when there are lower emissions from the emitting sources.[37–39] A few papers addressed diurnal pattern of mobile phone base station and reported no difference in exposure between morning and afternoon hours, but a difference between day and night time.[37,40] A personal measurement study with trained researchers in Belgium found that the day time exposure values in general are higher than night time values.[6] In a personal measurement study of Swiss adults,[4] personal exposure was about twice as high during the day (0.16 mW/m^2) than during night (0.08 mW/m^2). In the Dutch volunteer study,[30] daytime exposure was 0.183 mW/m^2 but during night it was about half (0.095 mW/m^2), and in the evening it was about twice (0.382 mW/m^2) as high. Personal measurements studies are affected by body shielding to varying degrees, depending on where the devices are carried, for example, in a bag or on top of a backpack 20–30 cm away from the body.[16] Whereas measures against body shielding were taken in some exposimeter studies with trained researchers, such measures are less convenient for volunteers and thus not applied. This is expected to affect outdoor and public transportation measurements but most likely less home measurements, as in the latter case the device is usually not carried on the body. Also in terms of own mobile phone use, restrictions are difficult to be applied in personal measurement studies, which explains higher uplink contributions in home and outdoor measurements in these studies compared with spot measurement and trained researcher studies. In public transportation, own mobile phone is of minor relevance[28] and thus volunteer and trained researcher exposimeter measurements are similar in terms of uplink.

Despite all of the caveats discussed, the following key messages can be made about typical RF-EMF exposure in the European everyday environment. Typical exposure levels as well as maximum measured levels are far below guidelines as recommended by ICNIRP (41 V/m for 900 MHz, 58 V/m for 1800 MHz and 61 V/m for 2100 MHz). Highest exposure levels occur mainly in public transportation due to the contribution of uplink. RF-EMF exposure levels in trains, buses, trams and metro varied a lot and mean values were above 0.5 V/m in many studies. In outdoor environments exposure levels are typically around 0.5 V/m rarely exceeding 1 V/m. The most relevant contributor is downlink. Volunteer study may underestimate this contribution due to body shielding. Contribution of broadcasting is underestimated by exposimeter studies, since they do not capture all relevant frequencies. Exposure levels in homes are lower than outdoor and typical in the range of 0.1–0.4 V/m. There was no indication about distinct differences between countries. If differences exist, they are considerably smaller than the data variability that is introduced from the various study settings, measurement protocols and data analysis procedures including reporting of the study results. Similarly, no obvious temporal trend was visible for the time between 2005 and 2013. If there were such a trend, as for instance observed in a single study in urban outdoor microenvironments measured over a period of 2 years,[11] it would be masked in the overall heterogeneity of the results. An increasing trend of RF-EMF exposure in the eligible personal measurement studies with volunteers has most likely happened purely by chance given the short time period which is captured by these studies.

CONCLUSION

This study has shown that RF-EMF exposure measurement studies across Europe have used different approaches and procedures limiting the comparability between studies. A general pattern was found towards highest exposure levels in public transportation (~0.5–1.0 V/m) mainly due to uplink, followed by outdoor levels (~0.3–0.7 V/m) mainly due to downlink. Exposures at homes are typically in the range of 0.1–0.4 V/m with relevant contributions from downlink, uplink and DECT, whereas WLAN is relatively low. For better comparability between countries and for evaluation of time trends, a more harmonized approach between studies is needed.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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