Monitoring of electromagnetic field exposure in an international context

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Summary

Objectives: Electromagnetic field exposure to general people is a public health concern and a topic of debate globally. Electromagnetic field is non-ionizing part of electromagnetic spectrum that can further be divided into extremely low frequency (0- 10 MHz) EMF and radiofrequency (10-300 MHz) EMF based on frequency and corresponding wavelength. Both of these components are of a topic of public debate and a subject of on-going research. The most common sources of extremely low frequency fields are alternating current carried in wiring, household appliances, power lines, electrical wiring, and electrical equipment. Some common sources of radiofrequency fields are mobile phone handsets and mobile phone base stations. Hence the main goals of this thesis were to propose a validated 3D computer model for extremely low frequency magnetic field exposure assessment from overhead powerlines and to develop a novel method of assessing radiofrequency field exposure in different microenvironments. More specifically, this thesis was planned with four different objectives as below:

- To systematically review the radiofrequency electromagnetic field exposure situation in the European countries based on peer-reviewed articles on spot measurements, personal measurement with trained researchers, and personal measurement with volunteers studies.
- To test the suitability of microenvironmental measurement surveys with portable exposimeters for monitoring of radiofrequency electromagnetic field levels in various everyday microenvironments in Switzerland.
- To apply already tested radiofrequency electromagnetic field monitoring protocol to monitor radiofrequency electromagnetic field exposure from Switzerland to international microenvironments of Ethiopia, Nepal, South Africa, Australia and the United States of America
- To validate a 3D computer model, developed for the calculation of the absolute value of magnetic flux density from an overhead power line, with a 6 measurement campaign conducted every two months for a year time.

Methods: For the systematic review for radiofrequency electromagnetic field exposure in European countries, we systematically searched the ISI Web of Science for relevant literature published between 1st January, 2000 and 30th April, 2015 that assessed RF-EMF exposure levels by any of the methods; spot measurements, personal measurement with trained researchers and personal measurement with volunteers. For the non-ionizing radiation monitoring in Switzerland, we used ExpoM-RF device mounted on a backpack to assess radiofrequency electromagnetic field by walking through 51 different outdoor microenvironments from 20 different municipalities in Switzerland. Measurements were conducted between 25th March and 11th July 2014.

The non-ionizing radiation monitoring in international microenvironments used the tested protocol from non-ionizing radiation monitoring in Switzerland. The measurements in international microenvironments were taken using two different kinds of portable RF meter called “ExpoM-RF” and “EME Spy 201”. The measurements were conducted either by walking (Switzerland and Nepal) or driving a car with ExpoM-RF device mounted on its roof (Ethiopia, South Africa, Australia, and the United States of America) or mixed walking and driving (Ethiopia, South Africa, Australia). We selected 15 different microenvironments from Switzerland, 18 microenvironments from Ethiopia, 12 microenvironments from Nepal, and 17 microenvironments from South Africa, 24 microenvironments from Australia and 8 microenvironments from the United States of America. Each of the selected microenvironments was measure twice: between 10 March and 14 April 2017. For the powerline validation study, six measurements were taken every two month between January 2015 and December 2015 from two different locations on two different power lines in order to describe variation of extremely low frequency magnetic field exposure by different seasons of the year. The measurements were taken from the selected power lines for at least 48 hours from each line on each measurement day. The measurements were taken using EMDEX II, temperature logger, and ESTEC device.

Results: The systematic review yielded twenty one published studies that 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. The mean total RF-EMF exposure for spot measurements in European “Homes” and “Outdoor” microenvironments was 0.29 V/m and 0.54 V/m respectively. 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.

The non-ionizing radiation monitoring in Switzerland found mean RF-EMF exposure of 0.53 V/m in industrial zones, 0.47 V/m in city centers, 0.32 V/m in central residential areas, 0.25 V/m non-central residential areas, 0.23 V/m in rural centers and rural residential areas, 0.69 V/m in trams, 0.46 V/m in trains and 0.39 V/m in buses. Temporal correlation between first and second measurement of each path was high: 0.83 for total RF-EMF, 0.83 for all five mobile phone downlink bands combined, 0.54 for all five uplink bands combined and 0.79 for broadcasting.

The non-ionizing radiation monitoring internationally found mean RF-EMF exposure in all 5 countries varied between 0.94 V/m and 0.05 V/m. Mean total RF-EMF exposure was highest in Australia (0.94 V/m city centers) and lowest in South Africa (0.36 V/m in rural centers and rural residential areas). For outdoor areas major exposure contribution was from mobile phone base station. The mobile phone base stations contributed more than 65% in all measured microenvironments across the 5 countries.

The two components of the powerline validation study: feasibility study by a computer model and its validation by field measurement of extremely low frequency magnetic field found the estimated precision of the results to be of the order of 10 % to 25 %, and this large degree precision may be due to errors in the coordinates and heights. The both components of the study helped in identifying the input data necessary for large-scale modeling of magnetic fields from high-voltage power lines and how long-term temporal averages of the field can be computed.

Conclusion: The systematic review of radiofrequency electromagnetic field concluded that typical radiofrequency electromagnetic field exposure levels are substantially below regulatory limits. The non-ionizing radiation monitoring in Switzerland demonstrated that microenvironmental surveys using a portable device yields highly repeatable measurements, which allows monitoring time trends of RF-EMF exposure over an extended time period of several years and to compare exposure levels between different types of microenvironments. The non-ionizing radiation monitoring in international microenvironments further support the results from pilot study in Switzerland. The powerline validation study concluded the model agrees well with the measurement values, with average offsets in the range of a few percent. We also found that the precision of the results corresponds to the precision estimated during the pilot study.

1. Introduction and Background

This thesis sheds light on methods for assessing exposure to electromagnetic fields in everyday microenvironments. The method was developed and applied in six countries across five continents, between August 2014 and April 2017. The study comprised two components of EMF: Radiofrequency Electromagnetic Field (RF-EMF) and Extremely Low Frequency Magnetic Field (ELF-MF).

1.1.Electromagnetic Field

The term “Electromagnetic field” (EMF) refers to a physical field, combining an electric field and a magnetic field produced by electrically charged particles. The charged particles may undergo ionization caused by the release of electrons from the atomic structure, or may give off non-ionizing radiation caused by the vibration of molecules (Levy, Wegman, Baron, & Sokas, 2011). EMFs are associated with the non-ionizing part of the electromagnetic spectrum (Figure 1) and can further be divided into low frequency (0- 10 MHz) EMF and radiofrequency (10-300 MHz) EMF, based on oscillation per second (frequency) and corresponding wavelength.

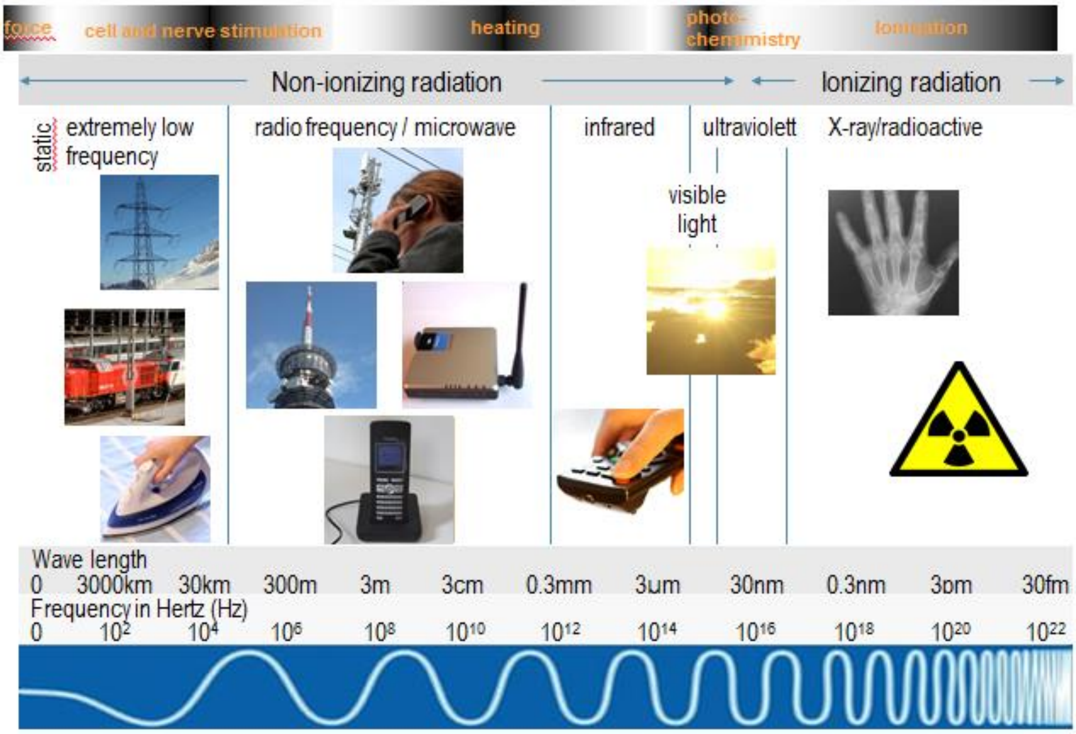

Figure 1: Electromagnetic Spectrum

As mentioned above, EMFs are produced by the interaction of electric and magnetic fields (Tipler & Mosca, 2004), as illustrated in Figure 2.

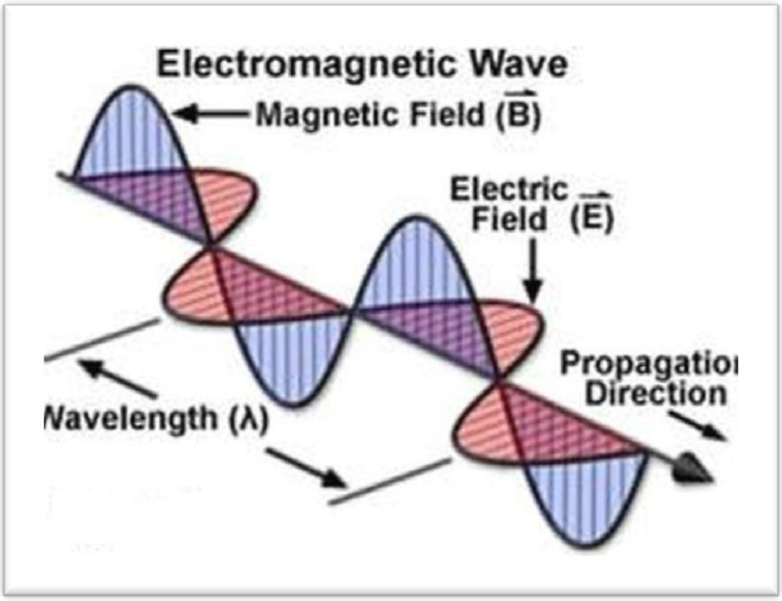

Figure 2: Propagation of Electromagnetic Wave (Source: https://www.quora.com)

EMFs are measured using electric field strength (E) by volt per meter (V/m) or power flux density by Watt per square meter (W/m^2). EMFs have two different sources: natural sources, such as the magnetic field of the earth's crust and human-made sources, such as mobile phone handsets, TV antennas, radio stations or mobile phone base stations.

1.1.1 Extremely Low Frequency Electromagnetic Field

Extremely low frequency (ELF) fields comprise 1 Hz to 300 Hz of non-ionizing radiation of the electromagnetic spectrum. The most common sources of ELF fields are alternating currents carried in household appliances, power lines, electrical wiring, and electrical equipment. Some other important sources are power plants and substations, welding machines, induction heaters and railway, tramway and subway systems (Protection, N.I.R., 2007). ELF fields also possess an electric and a magnetic component; an electric field is the force created by the attraction and repulsion of electric charges (the cause of electric flow), while a magnetic field is a force created as a result of moving charges (flow of electricity). The electric field is measured in volts per meter (V/m) and the strength of magnetic field is measured in tesla (T). The field strength of both electric and magnetic fields is directly related to the distance of the field source, i.e. the field strength decreases with distance from the field source (Ahlbom et al., 2008).

1.1.2 Radiofrequency Frequency Electromagnetic Field

Radiofrequency (RF) EMFs comprise any of the electromagnetic wave frequencies that lie in the range from below 3 kilohertz to about 300 gigahertz. This range of frequencies is used for communications signals, to transfer wireless information over long distances between a transmitter (such as mobile phone base stations and broadcasting transmitters) and a receiver (such as mobile phone handsets, radios and televisions). The direction of the signal is indicated by the terms downlink and uplink; downlink refers to communication from a mobile phone base station to a mobile phone handset and uplink refers to communication from a mobile phone handset to mobile phone base stations. Most relevant radiofrequencies used in recent telecommunication, along with their frequency range, are listed in Table 1.

Table 1: Overview of Frequency Bands

Frequency bands in Switzerland, Ethiopia, Nepal, South Africa and Australia	**Frequency range**	**Frequency bands in the United States of America**	**Frequency range**
FM Radio	88 – 108 MHz	FM	88-108 MHz
TV3	174 – 223 MHz	TV-VHF	174-216 MHz
TV4&5	470 – 790 MHz	TV-UHF	470-644 MHz
Mobile 800 MHz downlink	791 – 821 MHz	LTE Band 12 UL	698-716 MHz
Mobile 800 MHz uplink	832 – 862 MHz	LTE Band 12 DL	728-746 MHz
Mobile 900 MHz uplink	880 – 915 MHz	LTE Band 13 DL	746-756 MHz
Mobile 900 MHz downlink	925 – 960 MHz	LTE Band 13 UL	777-787 MHz
Mobile 1800 MHz uplink	1710 – 1785 MHz	LTE Band 5 UL	824-849 MHz
Mobile 1800 MHz downlink	1805 – 1880 MHz	LTE Band 5 DL	869-894 MHz
DECT	1880 – 1900 MHz	ISM / Smart meters	902-928 MHz
Mobile 2.1 GHz uplink	1920 – 1980 MHz	LTE Band 4 UL	1710-1755 MHz
Mobile 2.1 GHz downlink	2110 – 2170 MHz	LTE Band 2 UL	1850-1910 MHz
ISM 2.4 GHz	2400 – 2485 MHz	DECT 6.0	1920-1930 MHz
Mobile 2.6 GHz uplink	2500 – 2570 MHz	LTE Band 2 DL	1930-1990 MHz
Mobile 2.6 GHz downlink	2620 – 2690 MHz	LTE Band 4 DL	2110-2155 MHz
Mobile 3.5 GHz	3400 – 3600 MHz	LTE Band 40	2300-2400 MHz
ISM 5.8 GHz / U-NII 1-2e	5150 – 5875 MHz	WiFi 2G	2400-2483 MHz
		LTE Band 7 UL	2500-2570 MHz
		LTE Band 7 DL	2620-2690 MHz
		WiFi 5G	5150-5850 MHz

We are continually exposed to RF-EMF from two sources: near field sources and far field sources. Near field sources refer to the devices close to our body or those that we hold in our hand while communicating, such as mobile phone handsets and cordless phones. Far field sources correspond to telecommunication operating systems, such as mobile phone base stations and broadcast transmitters needed for mobile phone operation. Röösli et al., 2010a defined far field sources as radiation from a source located at a distance of more than one wavelength. We are exposed to RF-EMF from both near field sources and far field sources; however, near field sources cause up to 100 times higher exposure values than far field sources. Furthermore, the maximal energetic local absorption in the head from near field sources is about 1000 to 100,000 times higher during calls when compared to far field sources (Lauer et al., 2013). The power flux density is inversely proportional to the square of the distance from the source; hence, exposure decreases distance from the source increases. Although far field sources cause relatively lower exposure, the exposure is continuous and for longer durations (Frei et al., 2009a; Röösli et al., 2010b).

1.2. Methods of Exposure Assessment

Several methods have been used to assess exposure among the general population to RF-EMF levels in the environment, as described by Sagar et al., 2016. For example, propagation models have been used to predict the distribution of RF-EMF exposure emitted from fixed site transmitters. Various types of propagation models have been used in different contexts, like network planning and site selection or epidemiological studies (Beekhuizen et al., 2014; Bürgi et al., 2010; Bürgi et al., 2008; Neitzke et al., 2007). Such models are attractive, particularly because exposure can be assessed without involving study participants, which minimizes information and selection bias. However, these models fail to map exposure due to individual behavior and from sources where input data are not available, such as WLAN hotspots or other people’s wireless devices.

Another option for RF-EMF monitoring is conducting spot measurements. Spot measurements are conducted with stationary devices at one point in time at specific places. The advantage of such measurements is the possibility of strict adherence to the measurement protocol and the use of sophisticated measurement devices. However, this method is limited in terms of spatial resolution and population exposure; it does not take into account the behavior of people. Access to private places (homes) may be difficult to obtain and selection bias is of concern for representative sampling, which may be targeted in a monitoring study.

Additional bias could be introduced through the selection of the exact measurement place in a given setting. Analysis of temporal variability may be hampered by inaccuracy of the location of repeated spot measurements because RF-EMF may vary within a few centimeters.

Personal measurements of RF-EMF exposure are conducted using portable devices (Berg-Beckhoff et al., 2008; Blas et al., 2007; Bolte & Eikelboom, 2012; Frei et al., 2009b; Iskra et al., 2010; Joseph et al., 2010, 2008a; Knafl et al., 2008; Neubauer et al., 2007; Radon et al., 2006; Röösli et al., 2010; Thuróczy et al., 2008; Tomitsch et al., 2010; Urbinello & Röösli, 2013; Urbinello et al., 2014c; Urbinello et al., 2014a; Urbinello et al., 2014b). Small in size, exposimeters are carried by the participants and thus measure individual exposure during their daily activities. Exposimeters have been used to investigate the predictors of personal RF-EMF exposure (Ahlbom, Bridges, de Seze, et al., 2008; Bolte & Eikelboom, 2012; Patrizia Frei et al., 2009b, 2010; Neubauer et al., 2007a; Röösli et al., 2010). In these cases, study volunteers carry the exposimeter, fill in an activity diary and, ideally, geocodes are recorded by GPS during the study period. The advantage of personal measurement studies is that exposure distribution in the population is estimated directly and takes behavior into account. However, such measurements are demanding for volunteers and bias in the selection of volunteers is of concern. Personal measurement studies would be very costly for large collectives. Furthermore, data quality cannot be controlled and exposure recordings may be manipulated by putting the devices deliberately close to or far from known RF-EMF sources. Measurements are also influenced by the body of the person wearing the measurement device in such a way as to underestimate actual exposure (Blas et al., 2007; Bolte, van der Zande, & Kamer, 2011; Knafl et al., 2008; Neubauer et al., 2010; Radon et al., 2006). Another limitation is the lack of differentiation between exposure from one`s own mobile phone use and other people`s mobile phone use. Measurements taken during one`s own mobile phone use are not expected to represent the full extent of exposure (Inyang et al., 2008).

To overcome these limitations, microenvironmental measurement studies have been proposed (Röösli et al., 2010b). In this case, a portable radiofrequency meter is carried by a trained study assistant in different microenvironments such as residential areas, downtown areas, trains and railway stations, or shopping centers and data are collected with a high sampling rate (Urbinello et al., 2014c, 2014a, 2014b). Such a survey considers microenvironments as a unit of functional observation. Hence, it allows the collection of numerous spatially distributed measurements within a short time frame. Most importantly, adherence to the measurement protocol can be controlled and the data are collected exactly where people spend most of their time. The study assistant can conduct the measurement in a way that avoids body shielding and his or her own mobile phone can be switched off in order to focus on environmental RF-EMF exposure from other people's phones.

1.3. Telecommunication-Past and Present

Advancements in wireless communication technology have been rapid in the last two decades and, as a result, the exposure pattern to RF EMF in the everyday environment has changed significantly (Frei et al., 2009b; Neubauer et al., 2007; Röösli et al., 2010; Tomitsch et al., 2010; Urbinello et al., 2014b). Wireless communication technology started with second generation mobile phones (2G, GSM) with adaptive power control (APC), starting with maximal power output and down regulating the power output over time (Lonn et al., 2004). In the early 2000s, third generation mobile phones (3G, UMTS) were introduced with enhanced APC that yielded an average output power radiation 100 to 1000 times lower than previous models, or 1% of the maximum (Gati et al., 2009; Kelsh et al., 2011; Persson et al., 2012; Wiart et al., 2000). During the same decade, quad band phones (3G), also called smartphones, made internet accessible from mobile phones via web based applications, such as mobile television, push notification for emails and breaking news. To accommodate the changing smartphone technology and needs, newer wireless technology (fourth generation wireless technology, 4G), called Long Term Evolution (LTE), was introduced in the mid-2000s. 4G technology spread gradually to many countries and is still spreading all over the world. LTE has 3 to 4 times higher spectrum efficiency than UMTS and is allocated over 800 MHz, 1800 MHz and 2.6 GHz frequencies (LTE and LTE-Advanced factsheet "The Long Term Evolution of UMTS", 2015).

According to the most recent update from the International Telecommunication Union (ITU), the number of mobile phone subscribers reached more than 7.4 billion in 2016 globally, with 1.6 billion mobile phone subscribers in developed countries and 5.8 billion in developing countries. This figure varies for different regions of the world; 772 million subscribers in Africa, 426 million subscribers in the Arab States, 3.9 billion in Asia and Pacific, 405 billion in the Commonwealth of Independent States, 754 million in Europe and 1.1 billion in the Americas (ICT Facts and Figures, 2016). This figure is expected to increase further in coming years as wireless communication technology advances.

1.4.Regulatory Limits

Electromagnetic fields are ubiquitous and exposure patterns are complex. ICNIRP (The International Commission on Non-Ionizing Radiation Protection) proposes and publishes guidelines for limiting RF-EMF exposure to people with scientific consultation of experts in the field. ICNIRP is an independent organization that provides scientific advice and guidance to protect people and the environment against adverse effects of non-ionizing radiation. ICNIRP reference levels are frequency dependent and are based on the amount of energy absorbed by the human body in specific absorption rate (SAR). The frequency dependent reference levels recommended by ICNIRP are 10000 V/m (electric field strength) and 500 µT (magnetic flux density) for 50 Hz (i.e. extremely low frequency), 41 V/m for 900 MHz, 58 V/m for 1800 MHz and 61 V/m for 2100 MHz (ICNIRP, 1998). This guideline for limiting RF-EMF exposure levels have been adopted by more than 30 countries, mainly in Europe which is summarized in the Table. Americas (mainly North America) and some Asian countries consider SAR value of 1.6 W/kg averaged over 1gram of tissue for exposure from near field sources such as mobile phones as proposed by the Institute of Electrical and Electronic Engineers (https://www.ieee.org/index.html).

The World Health Organization is another important authority that has been working to protect the people from EMF exposure through its International EMF Project. The EMF project has been established with key objectives; to provide a coordinated international response to concerns about possible health effects of exposure to EMF, facilitate the development of internationally acceptable standards for EMF exposure, to provide information on the management of EMF protection programs for national and other authorities, including monographs on EMF risk perception, communication and management, and to provide advice to national authorities, other institutions, the general public and workers, about any hazards resulting from EMF exposure and any needed mitigation measures. The EMF project has maintained a database on EMF exposure reference values (http://www.who.int/docstore/peh-emf/EMFStandards/who-0102/Worldmap5.htm) that shows a large disparity of EMF exposure regulatory limits across various countries globally.

Table 2: Exposure limits for the general public for electromagnetic field for both ELF and RF-EMF in the countries of the European Union and some industrial nations outside Union (situation April, 2011)

Member states of the European Union											
	50 Hz (ELF)		900 MHz (GSM)			1800 MHz (GSM)			2100 MHz (UMTS)		
Country:	electric field strenth	magnetic flux density	electric field strenth	magnetic flux density	equivalent plain wave power density	electric field strenth	magnetic flux density	equivalent plain wave power density	electric field strenth	magnetic flux density	equivalent plain wave power density
	(V/m)	(μT)	(V/m)	(μT)	(W/m^2)	(V/m)	(μT)	(W/m^2)	(V/m)	(μT)	(W/m^2)
RECOMMENDATION 1999/519/EC	**5000**	**100**	**41**	**0.14**	**4.5**	**58**	**0.2**	**9**	**61**	**0.2**	**10**
Austria	[5000]	[100]	[41]	[0.14]	[4.5]	[58]	[0.20]	[9]	[61]	[0.20]	[10]
Belgium (Flanders)	—	*10*	*21* (1	—	—	*29* (1	—	—	*31* (1	—	—
Bulgaria	– (2	– (2	—	—	*0.1*	—	—	*0.1*	—	—	*0.1*
Cyprus	[5000]	[100]	41	0.14	4.5	58	0.2	9	61	0.2	10
Czech Republic	5000	100	41	0.14	4.5	58	0.2	9	61	0.2	10
Denmark	– (3	– (3	—	—	—	—	—	—	—	—	—
Estonia	5000	100	41	0.14	4.5	58	0.2	9	61	0.2	10
Finland	[5000]	[100]	41	0.14	4.5	58	0.2	9	61	0.2	10
France	5000 (4	100 (4	41	0.14	4.5	58	0.2	9	61	0.2	10
Germany	*5000*	*100*	*41*	*0.14*	*4.5*	*58*	*0.2*	*9*	*61*	*0.2*	*10*
Greece	5000	100	32 (5	0.11 (5	2.7 (5	45 (5	0.15 (5	5.4	47 (5	0.16 (5	6 (5
Hungary	5000	100	41	0.14	4.5	58	0.2	9	61	0.2	10
Ireland	[5000]	[100]	41	0.14	4.5	58	0.2	9	61	0.2	10
Italy	– (6	*3* (6	*6* (7	*0.02* (7	*0.1* (7	*6* (7	*0.02* (7	*0.1* (7	*6* (7	*0.02* (7	*0.1* (7
Latvia	—	—	—	—	—	—	—	—	—	—	—
Lithuania	*500* (8	—	—	—	*0.1*	—	—	*0.1*	—	—	*0.1*
Luxembourg	5000 (9	100 (9	41 (10	0.14	4.5	58 (10	0.2	9	61 (10	0.2	10
Malta	[5000]	[100]	41	0.14	4.5	58	0.2	9	61	0.2	10
Netherlands	– (11	– (11	—	—	—	—	—	—	—	—	—

Poland	*1000*	*75*	*7*	—	*0.1*	*7*	—	*0.1*	*7*	—	*0.1*
Portugal	5000	100	41	0.14	4.5	58	0.2	9	61	0.2	10
Romania	5000	100	41	0.14	4.5	58	0.2	9	61	0.2	10
Slovakia	*5000*	*100*	*41*	*0.14*	*4.5*	*58*	*0.2*	*9*	*61*	*0.2*	*10*
Slovenia	*500* (12	$_{10}$ (12	$_{13}$ (12	*0.04* (12	*0.45* (12	$_{18}$ (12	*0.06* (12	*0.9* (12	$_{19}$ (12	*0.06* (12	$_{1}$ (12
Spain	—	—	41	0.14	4.5	58	0.2	9	61	0.2	10
Sweden	$_{-}$ (13	$_{-}$ (13	[41]	[0.14]	[4.5]	[58]	[0.20]	[9]	[61]	[0.20]	[10]
United Kingdom	—	—	[41]	[0.14]	[4.5]	[58]	[0.20]	[9]	[61]	[0.20]	[10]
Industrial nations outside the European Union											
Australia	[5000] (14	[100] (14	41	0.14	4.5	58	0.2	9	61	0.2	10
Russia	*500*	*10*	—	—	*0.1*	—	—	*0.1*	—	—	*0.1*
Switzerland	—	$_{1}$ (15	$_{4}$ (16	—	—	$_{6}$ (16	—	—	$_{6}$ (16	—	—
U.S.A.	$_{-}$ (17	$_{-}$ (17	—	—	*6*	—	—	*10*	—	—	*10*

“All limits are given as root mean square (rms) value. Where necessary magnetic flux density was calculated from magnetic field strength using a magnetic permeability of 4π × 10-7 H/m. Normal typeface: reference level for the external field in the meaning of Recommendation 1999/519/EC, derived from basic restriction. Application is mandatory unless value is in square brackets. Italic typeface: mandatory exposure limit in terms of the external field outside the body.” Source: http://ec.europa.eu/health/electromagnetic_fields/docs/emf_comparision_policies_en.pdf

Notes:

1) Regional regulation; maximum per antenna in Flanders or per site in Brussels: 3.0 V/m at 900 MHz, 4.2 V/m at 1800 MHz, 4.5 V/m at 2100 MHz; maximum per antenna in Wallonia: 3 V/m

2) Minimal distances to power lines and to electrical distribution systems, differentiated by voltage; separate regulation for video display units

3) For new developments: agreement between local government and electricity sector to examine measures to reduce magnetic fields if average yearly exposure above 0.4 µT

4) For new or modified installations, technical conditions for electricity distribution

5) For antenna stations closer than 300 m to "sensitive" locations (schools, kindergartens, hospitals, care homes); elsewhere 35 V/m, 0.11 µT, 3.1 W/m2 at 900 MHz; 49 V/m, 0.16 µT, 6.3 W/m2 at 1800 MHz; 51 V/m, 0.17 µT, 7 W/m2 at 2100 MHz

6) For new installations near homes, schools, playgrounds; 10 µT for existing installations near homes, schools, playgrounds; 1999/519/EC for all other places

7) Near homes and their outdoor annexes, in schools and playgrounds, in places with stay greater than 4 hours; elsewhere 20 V/m, 0.06 μT, 1 W/m2

8) Limit inside homes; outside homes 1000 V/m; suburban green zone, roads 10000 V/m; uninhabited 15000 V/m

9) Security conditions for electricity lines; there are also voluntary minimal distances to power lines for new developments

10) Limit per antenna 3.0 V/m

11) Recommendation to local government: create no new situations of long-term stay of children in magnetic flux density greater than 0.4 μT around power lines

12) Applies to homes, hospitals, health resorts, public buildings, tourism buildings, schools, nurseries, playgrounds, parks, recreational areas; otherwise limit for external electric and magnetic field strength equal to reference level in 1999/519/EC; for power frequency limits apply to new or reconstructed sources only

13) Reduce exposure radically deviating from natural background when possible at reasonable expense with reasonable consequences

14) For continuous exposure; for few hours per day 10000 V/m and 1 mT; for few minutes per day more than 10000 V/m or 1 mT, provided basic restriction is met

15) For new installations at places of sensitive use (buildings in which persons stay for longer periods, playgrounds); for existing installations limit for external electric field strength and magnetic flux density as reference level in 1999/519/EC, but optimise order of phases at places of sensitive use

16) Limit per location for new and existing antenna installations at places of sensitive use (buildings in which persons stay for longer periods, playgrounds); limit for aggregate exposure from multiple antenna locations equal to reference level in 1999/519/EC

17) No federal regulation; limits are set in some states, other states have prudent avoidance policy (measures to reduce exposure of the population at reasonable cost)

1.5. Health Implication

1.5.1 Health Implication: Extremely Low Frequency Exposure

Exposure to electromagnetic field (RF and ELF) to general public has always been a controversial topic. The most common sources of ELF to the general public are in-house installations, household applinaces and power lines. People living inside residential buildings near the power lines are constantly exposed to ELF magnetic fields. Recent epidemiological studies have found increased health risks associated with magnetic field exposures near electric power lines (Grellier et al., 2014). The association between ELF MF exposure and health risk is not a new topic; it goes back to a study published in 1979 which concluded a possible association between childhood leukemia among people living near electric power lines (Wertheimer & Leeper, 1979). In the meanwhile numerous studies have been conducted and pooled analyses found consistent elevated risks for children exposed to magnetic fields above 0.3/0.4 µT (Greenland et al., 2000; Kheifets et al., 2010). Nevertheless, a plausible biological mechanism for these observations could not be identified in experimental and toxicological research and thus the IARC has classified ELF-MF as possible carcinogenic (2B) (International Agency for Research on Cancer, Working Group on the Evaluation of the Carcinogenic Risks to Humans, & Meeting. IARC Working Group on the Evaluation of Carcinogenic Risks to Humans, 2001). For adults the epidemiological data are less clear. For instance, in 2013 a large study concluded no epidemiological association between adult cancers with residential magnetic fields in proximity to high voltage overhead power lines (Elliott et al., 2013). On the other hand more recent studies on neurodegenerative diseases and ELF-MF found some indications for an association, in particular for Alzheimer diseases and amyotrophic lateral sclerosis (Liebl et al., 2015). The researchers in the field have been continuing to solve the puzzle between ELF exposure and potential health risk. If this association is proven even if this is weak, it will put millions of people at risk worldwide.

1.5.2 Health Implication: Radiofrequency Electromagnetic Field Exposure

The continuous societal industrialization and technological revolution has resulted in unprecedented increase in the number and diversity of radiofrequency (RF) electromagnetic field (EMF) sources like cellphone, cordless phone, cable lines and radio that operate in association with broadcast transmitters and mobile phone base stations. The use of these devices made the human lives much comfortable while on the other hand they pose some serious health risk due to their EMF emissions (Levallois et al., 2002). In recent years the use of wireless communication devices has increased exponentially throughout the world as described in the Chapter 1.3. The increasing figures of mobile phone handsets and operating mobile phone base stations have been associated with increased RF-EMF exposure to general public; however exposure levels are unknown.

In spite of rigorous studies, the question is not yet resolved whether exposure to radiofrequency (RF) electromagnetic field (EMF) in everyday life poses any health threats or not. Due to advancing technology, the exposure to electromagnetic fields these days are inevitable. Everyone is exposed to RF-EMF to a certain degree and even a small risk increase would cause substantial public health concern. Exposure assessments indicated that a large number of people felt affected by RF-EMF exposure and consider themselves to have some degree of electromagnetic hypersensitive; observed proportion were 3% in California (Levallois et al., 2002), 1.5% in Stockholm (Hillert et al., 2002), 5% in Switzerland (Schreier et al., 2006), 4% in England (Eltiti et al., 2007) and 10% in Germany (Blettner et al., 2008). However, several experimental studies applying a randomized cross-over design have been failed to establish causal link with acute RF-EMF exposure (Röösli et al., 2010a; Röösli & Hug, 2011; Rubin et al., 2005; Rubin et al., 2009).

One of the largest case control study has been the INTERPHONE study, conducted across 13 countries, using a common protocol, coordinated by the WHO found no observed increased risk associated with mobile phone use for different types of tumors. Although a statistically significant increased risk of glioma (OR: 1.40, 95%CI: 1.03-1.89) was found at the highest exposure levels for the 10th decile of the cumulative call duration (≥1640 hours), but failed to established the association (OR: 1.15, 95% CI: 0.81-1.62) for meningioma (The INTERPHONE Study Group, 2010). Brain tumors are the second most common type of tumors among children (Michel et al., 2007) and are vulnerable group than adults since children start using mobile phone earlier in life and consequently have a higher cumulative life time exposure (Böhler & Schüz, 2004). Such assumptions lead the researchers to conduct the CEFALO multi-center case control study among children and adolescents across Denmark, Sweden, Norway and Switzerland. The study found no increased risk of brain tumors for areas of the brain absorbing the highest amount of energy. Mobile phone users were not more diagnosed with brain tumors than non-users of mobile phones (OR: 1.36, 95%CI: 0.92-2.02). The children who had history of using mobile phone five years prior to the study were not at increased risk compared to non-users (OR: 1.26, 95%CI: 0.70-2.28).

Hence the study group concluded no causal association of mobile phone use and localization of brain tumors with an absence of an exposure-response relationship (Aydin et al., 2011).

Majority of the studies looking into association between use of mobile phones and brain tumors have not established a causal relationship (Ahlbom et al., 2009; Aydin et al., 2011; P. Frei et al., 2011; Repacholi et al., 2012; The INTERPHONE Study Group, 2010). The important reasons could be the fact that mobile phone use has increased exponentially in recent years, however, development of brain tumors or such condition takes several years of chronic exposure to EMF. The current state of research indicates no association between mobile phone use and increased health risk in the short term exposure (<10 years). A cohort study globally has been investigating possible health effects of the long term use of mobile phones and other wireless technologies. The aim of the study is to carry out long-term health monitoring of a large group of people to identify the unresolved issue of possible health risks linked to using mobile phones and other wireless technologies over a long period of time (Schüz et al., 2011).

2. State of Research and Objectives of the Thesis

2.1. Research Gaps

Mobile phone communication has been rising dramatically and is ubiquitous. New wireless telecommunication devices have revolutionized the communication world and lifestyle of people living in both developing and developed countries. With the evolution of newer smartphones, people are dependent on them for variety of task other than just making calls or texting. Several web based application are introduced every day for making the life easier such as mobile television (streaming), email access with push notification, alert of breaking news. Today, people do almost everything which was not possible ten years back and this has been altering radiofrequency electromagnetic field exposure. Changes in telecommunication have been made to adopt these newer technologies to appropriately functioning of new mobile phones with better coverage. The recent introduction of Long Term Evolution (4G) technology across cities of many countries globally has further predicted to expand the telecommunication network over coming years (Neubauer et al., 2007) to meet the demand of increasing usage of mobile phone and to fulfill the need of newer mobile phones to transfer high data rates for web based applications.

Advancement in wireless communication technology has been rapid in the last two decades and as a result the exposure pattern to radiofrequency electromagnetic field RF EMF has changed in the everyday environment significantly (Frei et al., 2009b; Neubauer et al., 2007; Röösli et al., 2010; Tomitsch et al., 2010; Urbinello et al., 2014b). This pattern will further continue to change in the future. According to the most recent update from the International Telecommunication Union (ITU), the number of mobile phone subscribers has reached more than 7.4 billion in 2016 which continues to increase in the coming years (ICT Facts and Figures, 2016). The impact of this increment on the RF-EMF exposure situation in the everyday environment is unknown.

Consequently, the World Health Organization (WHO) has recommended the quantification of personal RF-EMF exposure and identification of the determinants of exposure in the general population as a priority in their research agenda (World Health Organization, 2010). However, very little has been done to monitor EMF exposure situation of the population or specific environments. This is mainly due to the complex nature of exposure quantification and high temporal and spatial variability of RF-EMF levels in the environment (Bornkessel et al., 2007; Frei et al., 2009a; Joseph et al., 2008; Röösli et al., 2010). Several methods for EMF exposure assessment have already been described with their advantages and disadvantages in chapter 1.2 under the heading "Methods of Exposure Assessment"

2.2. Objectives

With all the above issues and concerns, the goals of this thesis were to developing new methodology both for better RF-EMF exposure assessment to general public and to propose a validated model for ELF exposure assessment from overhead powerlines. This thesis has been planned specifically with four different objectives as described below:

Objective 1: Systematic Review

To systematically review the RF-EMF exposure situation in the European countries based on peer-reviewed articles on spot measurements, personal measurement with trained researchers, and personal measurement with volunteers studies. Specifically, this objective aimed to derive exposure distribution functions for total RF-EMF exposure for population samples and specific microenvironments, to assess the contribution of different sources to total RF-EMF exposure at the population and microenvironmental level.

Objective 2: NIR Monitoring in Switzerland

To test the suitability of microenvironmental measurement surveys with portable exposimeters (PEM) for monitoring of RF-EMF levels in various everyday microenvironments in Switzerland. Specifically, it aimed at evaluating the repeatability and spatiotemporal variability of repeated measurements of 51 selected everyday microenvironments and to describe the exposure situations in these publicly accessible microenvironments.

Objective 3: NIR Monitoring Internationally

To apply already tested RF-EMF monitoring protocol from Switzerland to an international microenvironments of Ethiopia, Nepal, South Africa, Australia and the United States of America. This objective also aimed at comparing important microenvironments of each selected countries with respect to overall exposure levels and major sources of RF-EMF.

Objective 4: Powerline Study

To validate a 3D computer model, developed for the calculation of the absolute value of magnetic flux density from an overhead power line, with a 6 measurement campaign conducted every two months for a year time. Specifically, this objective aimed to compare measured annual average ELF-MF from overhead power lines with calculated ELF-MF values from the computer model. Also, to describe seasonal variation of ELF-MF over the year based on six measurement campaign conducted every two month over a year.

3. Methods

3.1.Systematic Review

We systematically search literature from Medline and ISI Web of Science for relevant literature published between 01 January 2000 and 30 April 2015. We used four set of words; “exposure characteristics”, “study subject/area”, “exposure assessment/measurement” and “radiation source” with various possible search terms alone and in combination. In addition, we also examined reference lists of eligible articles and named them as “Reference of selected articles”.

We included only original research articles published in English or in German as a full publication in a peer-reviewed journal. We considered only articles on radiofrequency electromagnetic field exposure assessment conducted in the 29 European countries. We included the articles that were spot measurements, personal measurements with trained researchers (microenvironmental), and personal measurement with volunteers using portable devices alone or in combination. The eligible study had to report (or enough data to allow derivation) mean exposure RF-EMF levels in at least one specified microenvironment. In case of double publication, 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, pure methodological papers and editorials were also not considered in this review. Studies which applied a non-representative sampling strategy (i.e. only looking for “high value” areas or micro-modeling around a few meters of an antenna tower) did neither meet the inclusion criteria. Some articles reporting modeled exposure only without measurements for validation were also excluded. We also excluded studies addressing health risk, human experimental study or in vivo/vitro experimental study.

The literature search was 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 of the eligible studies. The approved extraction sheet had two components; one component reporting types of study, frequency bands used, country of measurement, types of microenvironments (outdoor, indoor, shopping centers, bedroom), devised used, year of data collection, sampling method used and any inclusion/exclusion criteria. The second component reporting result 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 mobile phone base station), uplink (exposure from mobile phone handset), 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 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.

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

3.2.NIR Monitoring in Switzerland

We included 20 municipalities that represented the nine community types according to the Federal Office for Spatial Development (ARE) community typology (Figure 3) (http://www.geo.admin.ch/internet/geoportal/en/home/vis.html): major centers (3), secondary centers of big centers (3), medium sized centers (2), small centers (2), belt of major centers (2), the belt of medium sized centers (2), peri-urban rural communities (2), agricultural communities (2), and tourist communities (2).

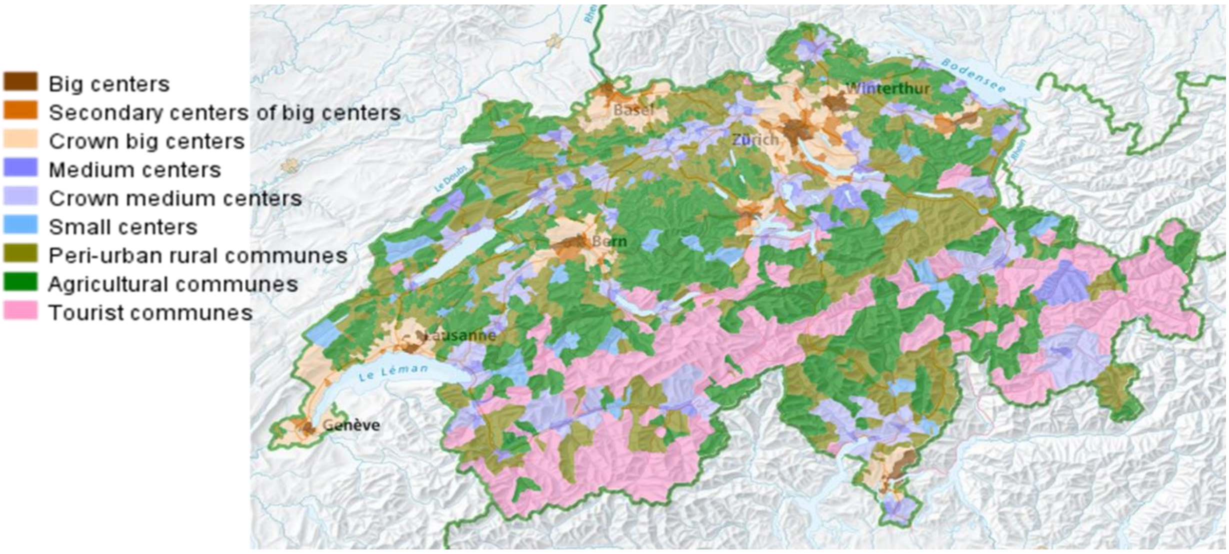

Figure 3: ARE Community Typology

From each of the 20 selected municipalities, 2-4 different microenvironments were selected for measurements (Table: 3). A total of 51 different microenvironments were selected to give a good representation of the entire country (5 city centers, 15 centers of rural areas, 5 central residential areas, 5 non-central residential areas, 15 rural residential areas, and 6 industrial areas).

Table 3: List of Municipalities and microenvironments

Muncipalities	Communty typology ARE	Microenviroments					
		City center	Rural center	Rural residential area	Central residential area	Non-central residential area	Industrial area
Nesslau-Neu St. Johann	Agricultural community		✔	✔			
Lungern	Agricultural community		✔	✔			
Zürich	Big center	✔			✔	✔	✔
Lugano	Big center	✔			✔	✔	
Lausanne	Big center			✔	✔	✔	
Rümlang	Crown big center		✔	✔			✔
St-Blaise	Crown medium center		✔	✔			
Gränichen	Crown medium center		✔	✔			
Neuchatel	Medium center	✔			✔	✔	
Aarau	Medium center	✔			✔	✔	✔
Seewen	Periurban rural community		✔	✔			
Frick	Periurban rural community		✔	✔			✔
Pully	Secondary center of big center		✔	✔			
Münchenstein	Secondary center of big center		✔	✔			
Dübendorf	Secondary center of big center		✔	✔			✔
Bioggio	Secondary center of big center		✔	✔			
Zweisimmen	Small center		✔	✔			
Watwil	Small center		✔	✔			✔
Brienz	Tourist community		✔	✔			
Gstaad (Saanen)	Tourist community		✔	✔			

City center and central residential area refer to the areas in cities with higher buildings (4 to 5 floors) and few road traffic as well as numerous people on the sidewalks. Non-central residential areas are outside the city center of cities with building heights of on average 2-3 floors and relatively larger proportions of green spaces compared to central residential areas and city center. The selected rural centers have a typical building height of 2 to 3 floors. Industrial areas refer to zones in cities and rural areas where industries are located. In addition to the outdoor areas, EMF measurements in public transport (bus, tram and train) during the journey of the study assistant to and from the measurement areas have been considered.

For the RF-EMF exposure assessment, an ExpoM-RF (Figure 4) portable measurement device was used. The ExpoM-RF was developed by Fields At Work (http://www.fieldsatwork.ch); a spin-off company from the Swiss Federal Institute of Technology in Zurich, Switzerland (ETH Zurich). This portable RF-meter is capable of quantifying RF-EMF exposure within 16 different frequency bands ranging from 87.5 to 5875 MHz. The upper limit of ExpoM-RF dynamic range is 5 V/m for all frequency bands except Mobile 3.5 GHz. The lower limit of the dynamic range varies for different frequency bands between 0.003 and 0.05 V/m (Table 4)

Figure 4: ExpoM-RF Device

Table 4: Overview of frequency bands and measuring range of ExpoM-RF

Frequency bands	**Frequency range**	**Dynamic range**	
FM Radio	87.5 – 108 MHz	0.02 V/m	5 V/m
DVB-T	470 – 790 MHz	0.005 V/m	5 V/m
Mobile 800 MHz downlink	791 – 821 MHz	0.005 V/m	5 V/m
Mobile 800 MHz uplink	832 – 862 MHz	0.005 V/m	5 V/m
Mobile 900 MHz uplink	880 – 915 MHz	0.005 V/m	5 V/m
Mobile 900 MHz downlink	925 – 960 MHz	0.005 V/m	5 V/m
Mobile 1800 MHz uplink	1710 – 1785 MHz	0.005 V/m	5 V/m
Mobile 1800 MHz downlink	1805 – 1880 MHz	0.005 V/m	5 V/m
DECT	1880 – 1900 MHz	0.005 V/m	5 V/m
Mobile 2.1 GHz uplink	1920 – 1980 MHz	0.003 V/m	5 V/m
Mobile 2.1 GHz downlink	2110 – 2170 MHz	0.003 V/m	5 V/m
ISM 2.4 GHz	2400 – 2485 MHz	0.005 V/m	5 V/m
Mobile 2.6 GHz uplink	2500 – 2570 MHz	0.003 V/m	5 V/m
Mobile 2.6 GHz downlink	2620 – 2690 MHz	0.003 V/m	5 V/m
Mobile 3.5 GHz	3400 – 3600 MHz	0.003 V/m	3 V/m
ISM 5.8 GHz / U-NII 1-2e	5150 – 5875 MHz	0.05 V/m	5 V/m

3.3.NIR Monitoring Internationally

NIR monitoring internationally was a continuation of NIR monitoring in Switzerland but with wider microenvironments from various countries such as Ethiopia, Nepal, South Africa, Australia and the United States of America. This multi-country RF-EMF monitoring considered unit of observation as microenvironment such as city centers, residential areas, non-central residential areas, industrial areas and so forth. The measurements were taken using three different kinds of portable RF meter called “ExpoM-RF v1”, “ExpoM-RF v3” and “EME Spy 201”. The two versions of ExpoM-RF (version 1: Expom and version 3: ExpoM-RF) were developed by Fields At Work (http://www.fieldsatwork.ch) and the EME Spy 201 was developed by developed by Microwave Vision Group, France, http://www.mvg-world.com/en).ExpoM-RF was used for RF-EMF exposure assessment in Switzerland, Ethiopia, Nepal, South Africa and Australia. EME Spy 201 was used in the United States of America due to differences in frequency bands in operation in the United States of America. The exposure assessment was conducted by only walking in Switzerland and Nepal, by only driving in the United States of America, and by walking and driving in Ethiopia, South Africa and Australia. A mobile phone with a TimeStamp App was used in flight mode to record the start and end times of each measurement while walking or driving. We selected 18 different microenvironments from Switzerland and Ethiopia, 12 microenvironments from Nepal, and 17 microenvironments from South Africa, 24 microenvironments from Australia and 8 microenvironments from the United States of America. Each of the selected microenvironments was measure twice: between 10 March and 02 April 2015 in Switzerland, between 27 September and 07 October 2015 in Ethiopia, between 08 November and 22 November, 2015 in Nepal, between 03 May and 26 May, 2016 in South Africa, between 30 September and 20 October, 2016 in Australia, and between 31 March and 14 April, 2017 in the United States of America.

3.4.Powerline Validation Study

This validation study focused on validating a 3D computer model with ambient level low-frequency magnetic fields from high voltage power lines in Switzerland. Six measurements were taken every two month between January 2015 and December 2015 from two different locations on two different power lines. The six measured ELF MF from the powerline provided a good average value and also the variation of the ELF-MF by seasons over the year. The ELF-MF emission based on seasons was measured to extrapolate the measurement as it depends upon line configuration and electric load in the cables. The cable line configuration varies by the temperature outside as a result the distance between ground and cables fluctuate. The distance between ground and cable lines was taken twice; before and after each measurement and height difference was calculated for each measurement. The measurements were taken from the selected power lines for at least 48 hours from each line on each measurement day. The measurements were taken using EMDEX II (Figure 5), temperature logger (Figure 6), and ESTEC device (Figure 7).

Figure 5: Emdex II

Figure 6: Temperature Logger

Systemzeit: 19:40:02 25/02/2013
DL-MW 10-Zeit: 19:40:02 25/02/2013
Startverhalten: Tastengesteuert
Startzeit: 01:00:00 01/01/1970
Stoppverhalten: Tastengesteuert
Stoppzeit: 01:00:00 01/01/1970
Anzeigeverhalten: XYZ Achse 5 Hz bis 2.000 Hz
LED-Verhalten: Messwert
Grenzwert für LED [nT]: 0
Buzzer-Verhalten: Immer aus
Grenzwert für Buzzer [nT]: 0

Figure 7: ESTEC Device

A total of seven EMDEX II, two temperature logger (one measures just temperature and the other measures temperature and humidity) and two ESTEC devices were used for the ELF-MF measurements. All the above devices were kept in a thermal box of 12 litre using phase change materials (PCM) packed in plastic bags to protect the devices from extreme weather, cattle passing by, and other similar unknown identities. We performed a lab test for testing all the devices being used. The results were not influenced by the thermal box. The phase change materials, however helped in variation of extreme temperature. That means, when five bags of phase change materials were used in the thermal box it slowed down the fall of the temperature significantly. Altogether nine thermal boxes will be prepared and placed between two towers beneath the cables as shown in the picture below (Figure 8).

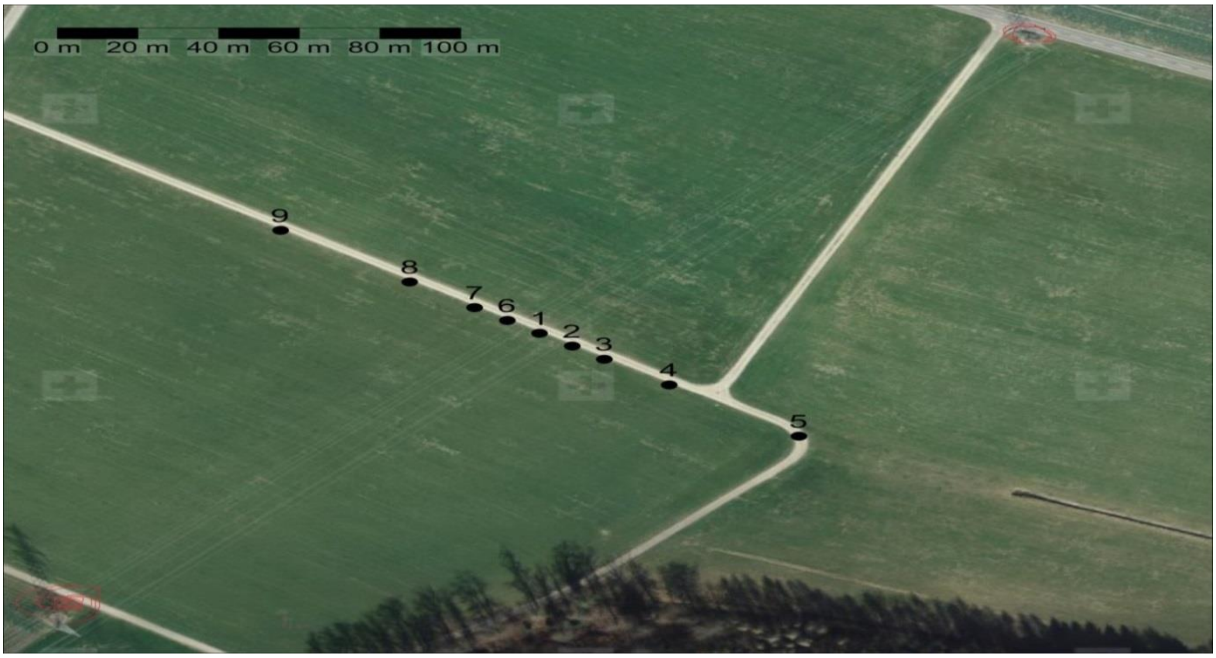

Figure 8: Arrangement of keeping Boxes

The distance between each of the boxes was different. The Box 1 was approximately at the perpendicular center of the two overhead power lines and distance between each of two other boxes corresponding to the Box 1(center) on either side of the Box 1. The distance between the Box 1 and Box 2 was 10m, between Box 1 and Box 3 was 20, between Box 1 and Box 4 was 40m and between Box 1 and Box 5 was 80m on the one side from the center. The same distance was applied on the other side of the center. That means the distance between the Box 1 and Box 6 was 10m, between Box 1 and Box 7 was 20, between Box 1 and Box 8 was 40m and between Box 1 and Box 9 was 80m. Each of the nine boxes comprised of different devices and materials in them. A and B are the two opposite sides from the center (Box1). The figure below (Figure 9) shows the content of the nine boxes:

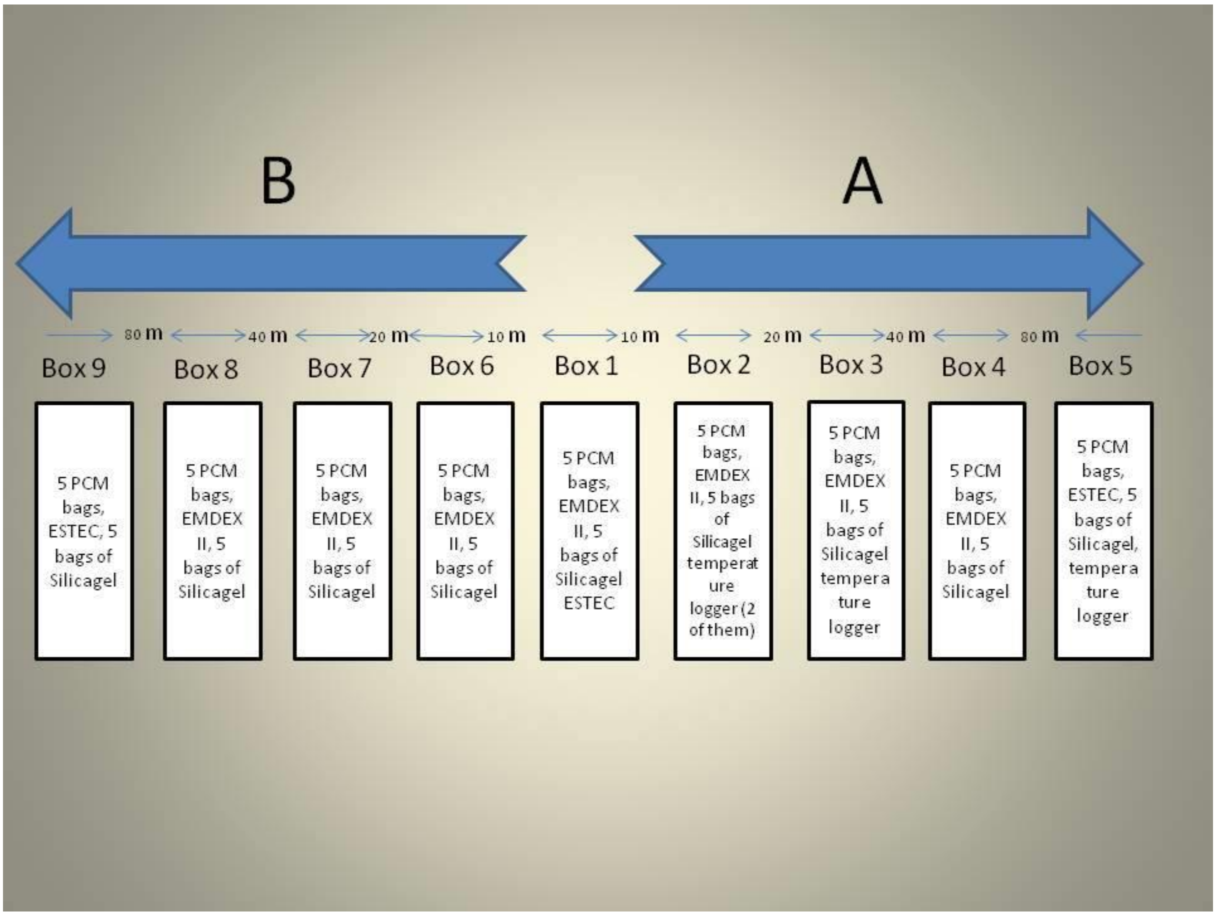

Figure 9: Content of the Boxes

The boxes with devices were deployed for 48 hours during weekdays with no maintenance scheduled by SWISSGRID. After the measurements, the devices were either turned off (ESTEC) or put in standby (EMDEX) and were brought back to ARIAS office Bern. The data processing and analyses were performed at the office. The data from EMDEX devices were downloaded with its own software program. The downloaded data were saved in CSV format and stored in a specific data file. The data from ESTEC devices were also downloaded and read with its own software program to be checked for any error and saved in CSV format in the data file. The data from temperature loggers were also downloaded with its own software and saved in CSV format in the data file.

For the validation of the study, the currency flow data for the measurement period were obtained from SWISSGRID for the same 48 hours and for each power line. The reported data from SWISSGRID were used to calculate ELF-MF and the location of each box, which then compared with measured ELF-MF data taken for 48 hours from the overhead power lines. Analyses were also performed to describe the variation in ELF-MF by seasons over the year and within 48 hours. Based on the measured and calculated data, we calculated annual average exposure from the selected two power lines. We also calculated and compared exposure by the distance of the cables. We also calculated average difference of the measured and calculated ELF MF values.

4. Results

4.1. Article 1: Radiofrequency electromagnetic field exposure in everyday microenvironments in Europe: a systematic literature review

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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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Keywords: exposimeters; microenvironment; mobile phone base station; mobile phone handset; radiofrequency electromagnetic fields (RF-EMF)

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

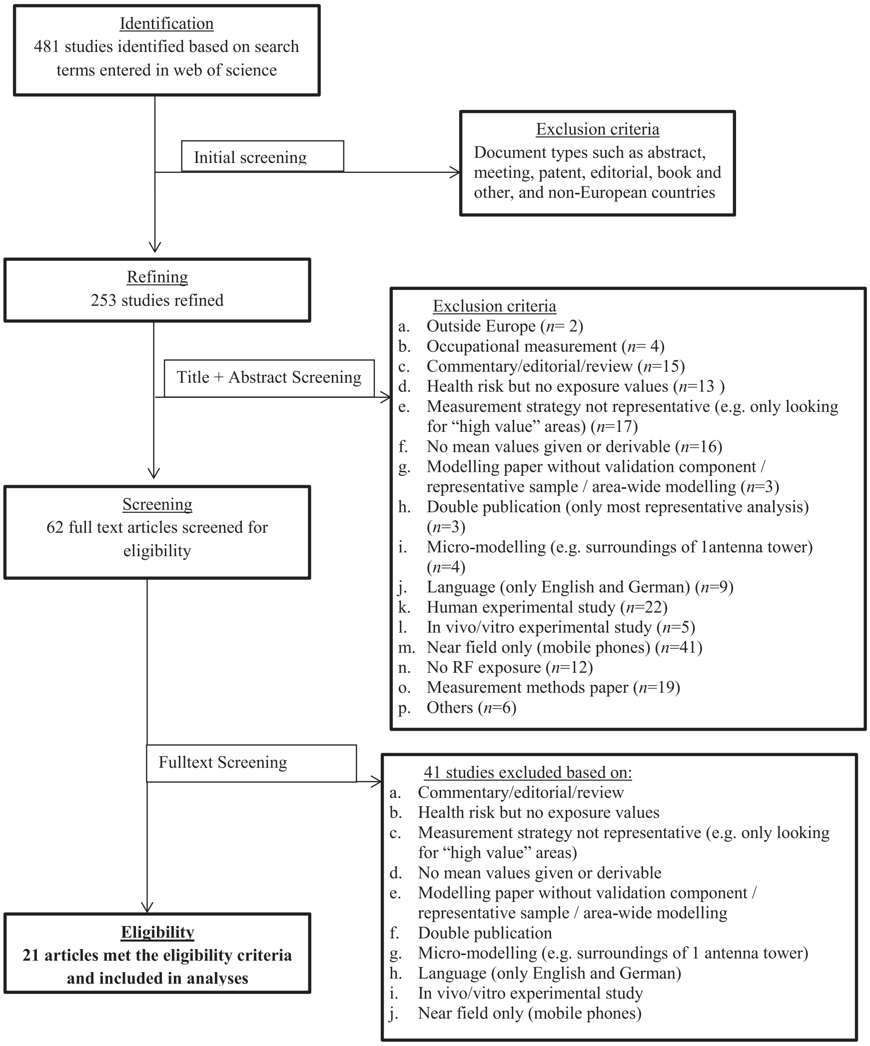

Figure 1. Flowchart showing the identification and selection of studies on radiofrequency electromagnetic field (RF-EMF) in European countries.

Table 1. Overview of 21 eligible studies.

			Type of measurement			Data collection
Country	*Study*	*ID*	*Spot measurement*	*Personal with trained resercher (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

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	✓	

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 microenvironment 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 microenvironments 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

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.

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			

Table 4. (Continued)

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*
			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			

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		

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			

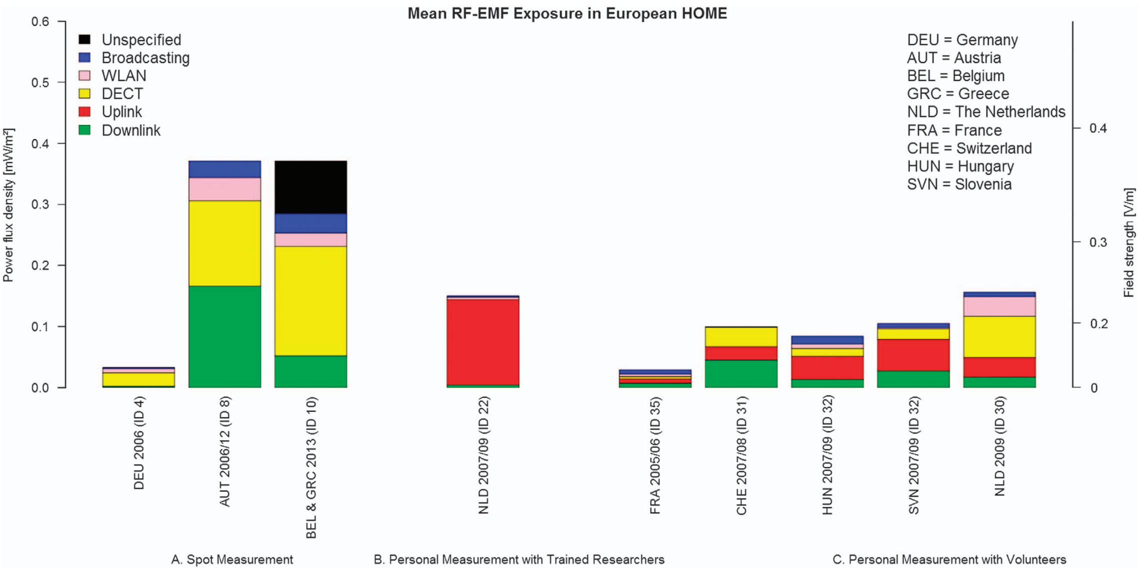

Figure 2. Mean radiofrequency electromagnetic field (RF-EMF) levels at "Home" across type of study (arranged chronically by spot measurement, personal measurement with trained researchers and personal measurement with volunteers).

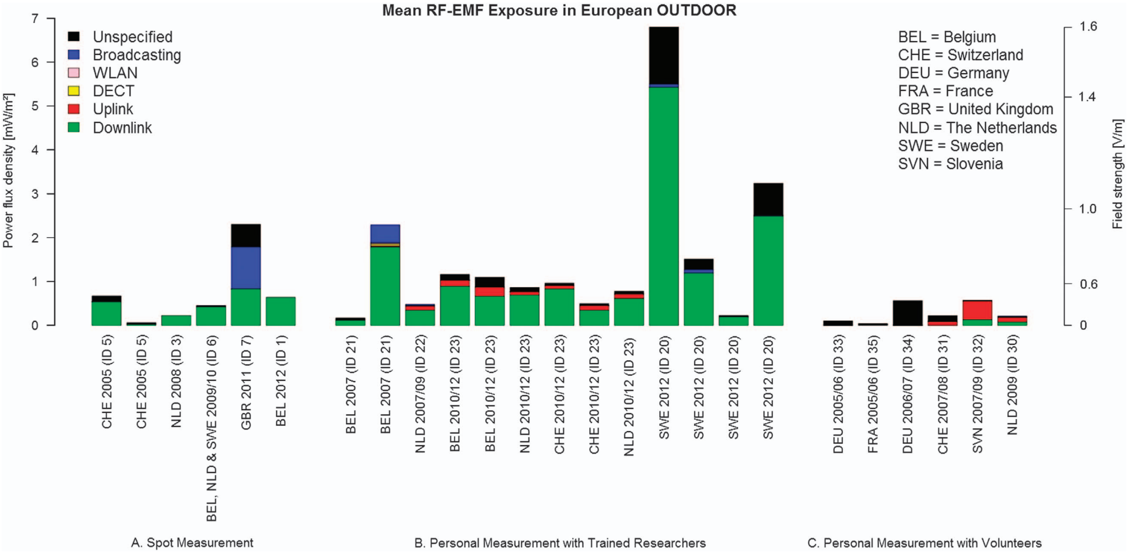

Figure 3. Mean radiofrequency electromagnetic field (RF-EMF) levels at "Outdoor" locations for different type of studies (arranged chronically by spot measurement, personal measurement with trained researchers and personal measurement with volunteers).

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

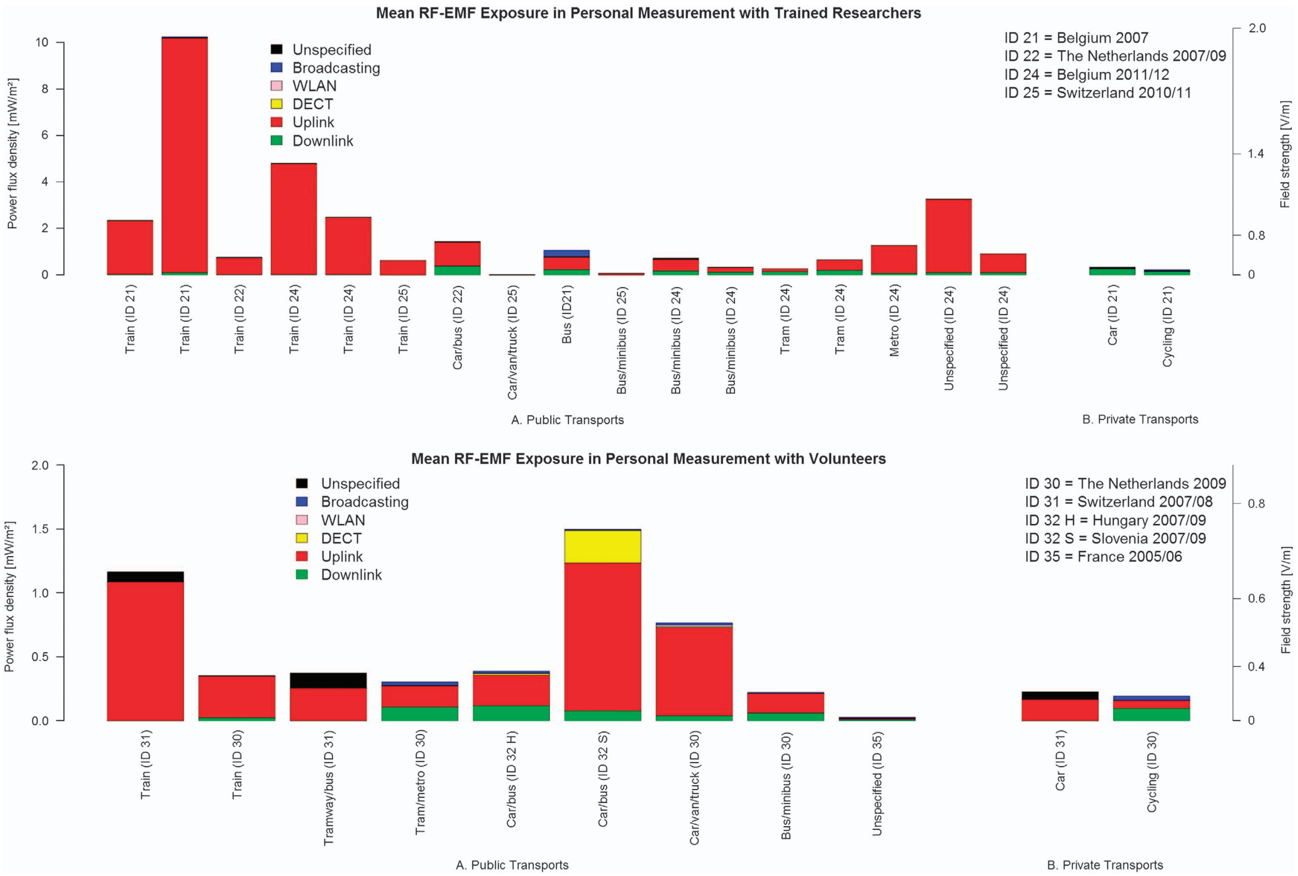

Figure 4. Mean radiofrequency electromagnetic field (RF-EMF) levels in public transportation across type of study (arranged chronically by personal measurement with trained researchers and personal measurement with volunteers).

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 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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Supplementary Information accompanies the paper on the Journal of Exposure Science and Environmental Epidemiology website (http://www.nature.com/jes)

Supplementary materials

Table S1: Search terminology

Searched terminology			
Exposure characteristics	**Study subject/area**	**Exposure assessment / measurement**	**Radiation source**
electric	child	exposimeter	base station
electromagnetic	general public	exposimetry	cell phone
electromagnetic field	human	exposure assessment	cellphone
EMF	individual	measurement	cellular phone
exposure	personal	PEM	cordless phone
field	population	personal dosimet* (the "*" is used for truncating search terms)	DECT cordless phone
non-ionising	resident	personal exposimet*	Global System for Mobile
non-ionizing	rural	personal exposure measurement	GSM
radio frequency	urban	personal exposure meter	mobile communication
radio frequency electromagnetic field		personal measurement	mobile phone
radiofrequency		RF measurement	mobile phone base station
radiofrequency electromagnetic field		spot measurement	phone base station
radiofrequency exposure			radio and television broadcast
RF			UMTS
RF electromagnetic field			Universal Mobile Telecommunications System
RF exposure			wireless LAN
RF-EMF			WLAN

Table S2: Summary of devices and microenvironments in Spot measurements studies

						Microenvironments	
Authors	**Country**	**ID**	**Authors**	**Devices used**	**Time (year of data)**	**Outdoor Microenvironments**	**Indoor Microenvironments**
Aerts et al., 2013	Belgium	1	Aerts et al., 2013	NBM-550 broadband field meter with an EF-0391 isotropic electric field probe	2012	Urban outdoor (schools, shops, restaurants, and other leisure spots)	
Beekhuizen et al., 2014	Netherlands	2	Beekhuizen et al., 2014	EMESPY 140	not mentioned	Outdoor unspecified	Indoor unspecified
Beekhuizen et al., 2015	Netherlands	3	Beekhuizen et al., 2015	EMESPY 140	2008	Urban outdoor	
Breckenkamp et al., 2012	Germany	4	Breckenkamp et al., 2012	EMESPY 120	2006		Bedroom only
Bürgi et al., 2008	Switzerland	5	Buergi et al., 2008	NARDA SRM-3000	2005	Outdoor unspecifed (urban and rural outdoor)	
Joseph et al., 2012a	Belgium, Netherlands, & Sweden	6	Joseph et al., 2012a	spectrum analyzer of type R&S FSL6, consisted of triaxial Rohde and Schwarz R&S TS-EMF Isotropic Antennas	2009-10		Indoor unspecified
Joseph et al., 2012b	United Kingdom	7	Joseph et al., 2012b	Tri-axial Rohde and Schwarz TS-EMF isotropic antennas	2011	Urban outdoor	
Tomitsch & Dechant, 2015	Austria	8	Tomitsch & Dechant, 2015	Spectrum analyser (MT8220A, Anritsu, Morgan Hill, CA) and two biconical antennas (SBA 9113 and BBVU9135þUBAA9114, Schwarzbeck, Schönau, Germany)	2006-2012		Bedroom, only
Verloock et al., 2010	Belgium	9	Verloock et al., 2010	Spectral analyzer and isotropic antenna (Narda NBM-550)	2009		Office (workplace)
Vermeeren et al., 2013	Belgium & Greece	10	Vermeeren et al., 2013	EME SPY 140 and EME SPY 121	2013		Home unspecified and Office unspecified

Table S3: Summary of devices and microenvironments in Personal measurements with trained researchers studies

					Microenvironments		
Authors	**Country**	**ID**	**Devices used**	**Year of Survey**	**Outdoor Microenvironments**	**Indoor Microenvironments**	**Public Transports**
Estenberg and Augustsson, 2014	Sweden	20	A spectrum analyzer (FSL 6; Rohde and Schwarz, Munich, Germany) and a three-axis measuring antenna (Satimo 30MHz–3 GHz; Rohde and Schwarz)	2012	Rural outdoor, Urban outdoor		
Joseph et al., 2008	Belgium	21	DSP120 EMESPY	2007	Rural outdoor, Urban outdoor	Urban indoor, Rural indoor	Trains, Bus, Car, Cycling
Joseph et al., 2010	Netherlands	22	EMESPY 120, EMESPY 121	2007-2009	Urban outdoor	Office (workplace), Home unspecified	Trains, Bus/minibus, Car/van/truck
Urbinello et al., 2014a	Belgium (Brussels) Belgium (Ghent) Switzerland (Basel 1st measurement) Switzerland (Basel 2 nd measurement) Netherlands (Amsterdam)	23	EMESPY 120	November, 2010-March, 2012	Urban outdoor (central residential area, non-central residential area and downtown)		
Urbinello et al., 2014b	Belgium (Brussels) Belgium (Ghent) Switzerland (Basel)	24	EMESPY 120	April, 2011-March, 2012		Indoor shopping mall, Airport , Railway station	Public transport unspecified, trains, Bus/minibus, metro, trams
Urbinello & Röösli 2013	Switzerland	25	EMESPY 120	January, 2010-January, 2011		Railway station	Train, Bus/minibus, Car/van/truck

Table S4: Summary of devices and microenvironments in Personal measurements with volunteers studies

				Microenvironments		
Authors	**Country**	**ID**	**Devices used**	**Outdoor Microenvironments**	**Indoor Microenvironments**	**Public Transports**
Bolte & Eikelboom, 2012	Netherlands	30	EMESPY 121	Outdoor, unspecified	Indoor, unspecified, Home unspecified , Bedroom only, Office (Workplace), Workplace unspecified (not restricted to office only), Indoor shopping mall, Railway station	Trains, Tram/metro, Bus/minibus, Car/van/truck, Bicycle
Frei et al., 2009	Switzerland	31	EMESPY 120	Outdoor unspecified, tramway	Home, Workplace, Friends place, leisure residence, Resturant, bar, Shopping mall, Sports halls, Cinema, University, Hospital, School building, Church, Airport	Car, Bus, Trains
Joseph et al., 2010	Hungary	32	EMESPY 120 and EMESPY 121	Urban outdoor	Office (workplace), Home unspecified,	Trains, Bus/minibus, Car/van/truck
	Slovenia					
	Switzerland					
Thomas et al. 2008 b	Germany	33	ESM-140	All areas unspecified		
Thomas et al. 2008a	Germany	34	ESM-140	All areas unspecified		
Viel et al., 2009	France	35	EMESPY 120		Home, Workplace	Transportation unspecified

4.2. Article 2: Use of portable exposimeters to monitor radiofrequency electromagnetic field exposure in the everyday environment

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Use of portable exposimeters to monitor radiofrequency electromagnetic field exposure in the everyday environment

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ABSTRACT

Background: Spatial and temporal distribution of radiofrequency electromagnetic field (RF-EMF) levels in the environment is highly heterogeneous. It is thus not entirely clear how to monitor spatial variability and temporal trends of RF-EMF exposure levels in the environment in a representative and efficient manner. The aim of this study was to test a monitoring protocol for RF-EMF measurements in public areas using portable devices.
Methods: Using the ExpoM-RF devices mounted on a backpack, we have conducted RF-EMF measurements by walking through 51 different outdoor microenvironments from 20 different municipalities in Switzerland: 5 different city centers, 5 central residential areas, 5 non-central residential areas, 15 rural residential areas, 15 rural centers and 6 industrial areas. Measurements in public transport (buses, trains, trams) were collected when traveling between the areas. Measurements were conducted between 25th March and 11th July 2014. In order to evaluate spatial representativity within one microenvironment, we measured two crossing paths of about 1 km in length in each microenvironment. To evaluate repeatability, measurements in each microenvironment were repeated after two to four months on the same paths.
Results: Mean RF-EMF exposure (sum of 15 main frequency bands between 87.5 and 5,875 MHz) was 0.53 V/m in industrial zones, 0.47 V/m in city centers, 0.32 V/m in central residential areas, 0.25 V/m non-central residential areas, 0.23 V/m in rural centers and rural residential areas, 0.69 V/m in trams, 0.46 V/m in trains and 0.39 V/m in buses. Major exposure contribution at outdoor locations was from mobile phone base stations (> 80% for all outdoor areas with respect to the power density scale). Temporal correlation between first and second measurement of each area was high: 0.89 for total RF-EMF, 0.90 for all five mobile phone downlink bands combined, 0.51 for all five uplink bands combined and 0.79 for broadcasting. Spearman correlation between arithmetic mean values of the first path compared to arithmetic mean of the second path within the same microenvironment was 0.75 for total RF-EMF, 0.76 for all five mobile phone downlink bands combined, 0.55 for all five uplink bands combined and 0.85 for broadcasting (FM and DVB-T).
Conclusions: This study demonstrates that microenvironmental surveys using a portable device yields highly repeatable measurements, which allows monitoring time trends of RF-EMF exposure over an extended time period of several years and to compare exposure levels between different types of microenvironments.

1. Introduction

Advancement in wireless communication technology has been rapid in the last two decades and as a result the exposure pattern to radiofrequency (RF) electromagnetic field (EMF) has changed in the everyday environment significantly (Frei et al., 2009b; Neubauer et al., 2007; Röösli et al., 2010; Tomitsch et al., 2010;

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Urbinello et al., 2014b). This pattern will further continue to change in the future. According to the most recent update from the International Telecommunication Union (ITU), the number of mobile phone subscribers has reached more than 7.0 billion in 2015 which continues to increase in the coming years (ICT Facts and Figures, 2015). The impact of this increment on the RF-EMF exposure situation in the everyday environment is unknown.

Consequently, the World Health Organization (WHO) has recommended the quantification of personal RF-EMF exposure and identification of the determinants of exposure in the general population as a priority in their research agenda (World Health Organization, 2010). However, very little has been done to monitor EMF exposure situation of the population or specific environments. This is mainly due to the complex nature of exposure quantification and high temporal and spatial variability of RF-EMF levels in the environment (Bornkessel et al., 2007; Frei et al., 2009a; Joseph et al., 2008; Röösli et al., 2010).

Several methods have been used for exposure assessment and monitoring of RF-EMF levels in the environment; propagation models have been used to predict the distribution of RF-EMF exposure emitted from fixed site transmitters. Various different types of propagation model have been used in different contexts like network planning and site selection or epidemiological studies (Beekhuizen et al., 2014; Bürgi et al., 2010, 2008; Neitzke et al., 2007). Such models are attractive, particularly because exposure can be assessed without the involvement of study participants which minimizes information and selection bias. However, such models fail to map exposure situation of individual behavior and of sources where input data are not available such as WLAN hotspots or other people's wireless devices.

Another option for RF-EMF monitoring is conducting spot measurements (e.g. Berg-Beckhoff et al., 2008, Tomitsch et al., 2010). Spot measurements are conducted at one point-in-time at specific places with stationary devices. The advantage of such measurements is the possibility of strict adherence to the measurement protocol and the use of sophisticated measurement devices. However, this method is limited in the spatial resolution and in terms of population exposure; it does not take into account the behavior of the people. Access to private places (homes) may be difficult to obtain, and selection bias is of concern for representative sampling, which may be aimed in a monitoring study. Additional bias could be introduced by the selection of the exact measurement place in a given setting. Analysis of temporal variability may be hampered by inaccuracy of the location of repeated spot measurements because RF-EMF may vary within a few centimeters.

Personal measurements of RF-EMF exposure are conducted using portable devices (Blas et al., 2007; Bolte and Eikelboom, 2012; Frei et al., 2009b; Iskra et al., 2010; Joseph et al., 2010, 2008; Knafl et al., 2008; Neubauer et al., 2007; Radon et al., 2006; Röösli et al., 2010; Thuróczy et al., 2008; Urbinello and Röösli, 2013; Urbinello et al., 2014a, 2014a, 2014b). Being small enough in size, exposimeters are carried by the participants and thus measure the exposure during their daily life activities. As a result, exposimeters have been used to investigate the predictors of personal RF-EMF exposure (Ahlbom et al., 2008; Bolte and Eikelboom, 2012; Frei et al., 2009b, 2010; Neubauer et al., 2007; Röösli et al., 2010). In a personal measurement, study volunteers carry the exposimeter, fill in an activity diary and ideally geocodes are recorded by GPS during the study period. The advantage of such personal measurement studies is that direct estimation of the exposure distribution in the population is obtained taking into account their behavior. However, such measurements are demanding for volunteers and bias in the selection of volunteers is of concern. They would be very costly for large collectives. Furthermore, data quality cannot be controlled and exposure recording may be manipulated by putting the devices deliberately close or far from known RF-EMF sources. Measurements are also influenced by the body of the person wearing the measurement devices that lead to underestimation of actual exposure (Blas et al., 2007; Bolte et al., 2011; Knafl et al., 2008; Neubauer et al., 2010; Radon et al., 2006). Another limitation is the lack of differentiation between exposure from one's own mobile phones use and other people's mobile phone use. Measurements taken during one's own mobile phone uses are not expected to represent the true exposure of the person (Inyang et al., 2008).

To overcome these limitations, microenvironmental measurement studies have been proposed (Röösli et al., 2010). In this case a portable radiofrequency meter is carried by a trained study assistant in different microenvironments such as residential areas, downtown areas, trains and railway stations or shopping centers and data are collected with a high sampling rate (Urbinello et al., 2014a, 2014b, 2014c). Such a survey considers microenvironments as a unit of functional observation. Hence, it allows the collection of numerous spatially distributed measurements within a short time frame. Most importantly, adherence to the measurement protocol can be controlled and the data are collected exactly where people spend most of their time. The study assistant can conduct the measurement in a way that avoids body shielding and his own mobile phone can be switched off in order to focus on environmental RF-EMF exposure from other people's phones.

To evaluate the suitability of microenvironmental measurement surveys with portable exposimeters (PEM) for monitoring of RF-EMF levels in Switzerland, a protocol for repeated measurements in various microenvironments has been developed. The aim of this study was to evaluate the repeatability and spatiotemporal variability of such measurements with respect to RF-EMF monitoring and to describe the exposure situations in these publicly accessible microenvironments.

2. Methods and materials

2.1. Site selection and description of microenvironments

We included 20 municipalities that represented the nine community types according to the Federal Office for Spatial Development (ARE) community typology (http://www.geo.admin.ch/internet/geoportal/en/home/vis.html): major centers (3), secondary centers of big centers (3), medium sized centers (2), small centers (2), belt of major centers (2), the belt of medium sized centers (2), peri-urban rural communities (2), agricultural communities (2), and tourist communities (2). From each of the 20 selected municipalities, 2–4 different microenvironments were selected for measurements (Supplementary material: Table S1). A total of 51 different microenvironments were selected to give a good representation of the entire country (5 city centers, 15 centers of rural areas, 5 central residential areas, 5 non-central residential areas, 15 rural residential areas, and 6 industrial areas). City center and central residential area refer to the areas in cities with higher buildings (4–5 floors) and few road traffic as well as numerous people on the sidewalks. Non-central residential areas are outside the city center of cities with building heights of on average 2–3 floors and relatively larger proportions of green spaces compared to central residential areas and city center. The selected rural centers have a typical building height of 2–3 floors. Industrial areas refer to zones in cities and rural areas where industries are located. In addition to the outdoor areas, EMF measurements in public transport (bus, tram and train) during the journey of the study assistant to and from the measurement areas have been considered.

2.2. Measurement device

For the RF-EMF exposure assessment, an ExpoM-RF portable measurement device was used. The ExpoM-RF was developed by Fields At Work (http://www.fieldsatwork.ch); a spin-off company from the Swiss Federal Institute of Technology in Zurich, Switzerland (ETH Zurich). This portable RF-meter is capable of quantifying RF-EMF exposure within 16 different frequency bands ranging from 87.5 to 5875 MHz. The upper limit of ExpoM-RF dynamic range is 5 V/m for all frequency bands except Mobile 3.5 GHz. The lower limit of the dynamic range varies for different frequency bands between 0.003 and 0.05 V/m (Supplementary material: Table S2). EXPOM-RF devices depict also values outside the sensitivity range depending on the calibration setting of each device. To avoid bias between devices, we thus censored values >5 V/m (upper detection limit) at 5 V/m. The values below half of the lower quantification limit were set to half of the lower quantification limit. The Wifi 5 GHz band has a lower quantification limit of 0.05 V/m – 10 times higher than for most of the other bands (Supplementary material: Table S2). This difference may lead to an overestimation of Wifi 5 GHz exposure with our approach of handling values outside the dynamic range of the device. However due to the fact that the potential overestimation of Wifi 5 GHz exposure remained a negligible ($<1\%$) part of the total exposure we abstained from using more elaborated methods like robust ROS (Röösli et al., 2008) and applied our simple approach to all bands. The device measures values based on a root mean square detector and has an isotropy of ca. 3 dB. The ExpoM-RF also has an inbuilt GPS. ExpoM-RF was calibrated at Fields At Work in an anechoic chamber twice; before the start of the measurement by the first study assistant and the second study assistant respectively.

2.3. Measurement procedure

The measurements were carried between 25th March and 11 July 2014 by two different trained study assistants. The first person took the measurements in March and April, the second person in May, June and July. Each microenvironment was comprised of two different paths i.e. path 1 and path 2 (possibly non-overlapping but preferably intersecting). Each path measures a length of about 1 km to be covered by walking in approximately 15 min. A measurement was taken every four second. The person taking the measurements was instructed to use the right hand side of the road whenever suitable. The study assistants were further instructed to turn off the personal mobile phone during the measurements. A mobile phone with a TimeStamp App was used in flight mode to record the start and end times of each walk along a predefined path. Most of the measurements were taken during weekdays except the first measurement in Aarau, Lausanne and Pully (Aarau on Saturday, Lausanne and Pully on Sunday). To track the assigned path when walking, the inbuilt GPS of the ExpoM-RF was used. ExpoM-RF was placed on the top of the backpack approximately 20–30 cm away from body so as to minimize the body shielding and to ensure the mobility.

2.4. Statistical analysis

We considered five relevant frequency groups: i) Uplink (mobile phone handset exposure): sum of mean power densities of all uplink frequencies (LTE800 Uplink), (Uplink900), (Uplink1800), (Uplink1900), and (LTE2600 Uplink); ii) Downlink (mobile phone base station exposure): sum of mean power densities of all downlink frequencies (LTE800 Downlink), (Downlink900), (Downlink1800), (Downlink2100), and (LTE2600 Downlink); iii) Broadcasting: sum of mean power densities of all the radio spectrum used for broadcasting (FM), and (DVB-T); iv) others; sum of mean power densities of frequency namely (DECT), (WLAN; ISM 2.4 GHz), and (WLAN; ISM 5.8 GHz). v) total RF-EMF exposure: sum of mean power densities of all frequency bands except (WiMax 3.5 GHz). We excluded WiMax 3.5 GHz since it is not used in Switzerland.

Summary statistics including arithmetic mean values and standard deviation were calculated for each path in the outdoor environments and for each type of public transportation. Differences between first and second measurements and between the measurements from both paths within a microenvironment were calculated to address repeatability and representativeness of the measurements. Further, Spearman correlation coefficients were calculated. All calculations were done using power flux density scale (mW/m^2) and results were then back-transformed to electric field strength (V/m) for all measurements. The Spearman correlation coefficients were calculated on the V/m scale. All analyses were done by statistical software R version 3.1.3 (https://www.r-project.org/). For planning a future RF-EMF monitoring study and to make predictions about the expected precision of average RF-EMF exposure for a specific type of microenvironment, we predicted the total RF-EMF mean values $\pm 95\%$ confidence intervals for different numbers of measurements per type of microenvironment based on the observed data distribution of our measurement survey (i.e. mean value and standard deviation).

3. Results

3.1. Characteristics of RF-EMF exposure level in different types of microenvironments

Fig. 1 summarizes mean RF-EMF exposure level for total RF-EMF, uplink, downlink and broadcasting per type of microenvironment. Mean total RF-EMF exposure (sum of 15 main frequency bands between 87.5 and 5875 MHz except WiMax 3.5 GHz) was 0.53 V/m in industrial areas, 0.47 V/m in city centers, 0.32 V/m in central residential areas, 0.25 V/m in non-central residential areas and 0.23 V/m in rural centers and rural residential areas. In public transport mean exposure was 0.39 V/m in buses, 0.46 V/m in trains and 0.69 V/m in trams (Table 1). At outdoor locations and in trams, the largest contribution was from downlink: city centers (96%), industrial areas (94%), rural centers (91%), rural residential areas (89%), non-central residential area (86%) and central residential area (83%). In public transport, mobile phone base stations contributed about 44% in bus, 33% in train and 70% in tram to the total exposure. Corresponding contributions of uplink exposure from mobile phone handsets were 40% in bus, 66% in train and 28% in tram. The exposure from WLAN (ISM 2.4 GHz and ISM 5.8 GHz combined) was generally very low but found to be highest in trams (0.05 V/m). The exposure from broadcasting was found highest in central residential areas (0.13 V/m) and industrial areas (0.12 V/m). The lowest exposure from broadcasting was observed in rural centers (0.06 V/m).

3.2. Variability of RF-EMF exposure levels within the same type of microenvironment

Table 2 summarizes the variability of downlink, uplink, broadcasting and total RF-EMF exposure level between different outdoor microenvironments within the same type of microenvironment. For total RF-EMF highest variability was seen for rural centers (minimum 0.062 V/m, median 0.171 V/m, maximum 0.569 V/m and coefficient of variation 1.327) and rural residential areas (minimum 0.056 V/m, median 0.186 V/m, maximum 0.526 V/m and coefficient of variation 1.318). Lowest variability

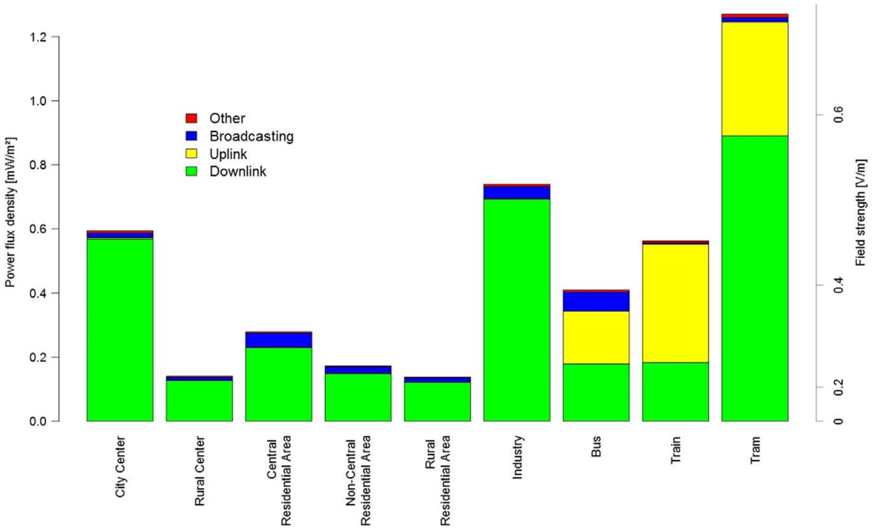

Fig. 1. Mean RF-EMF exposure per type of microenvironment and contribution from the four main groups of frequency bands. Note that the source contributions are only additive in units of power flux density.

Table 1
Average exposure levels per type of microenvironments including public transports (all values are in V/m).

Frequency bands	**Microenvironments**						**Public transports**		
	City center	Rural center	Central residential	Non-central residential	Rural residential	Industry	Bus	Train	Tram
FM	0.064	0.039	0.121	0.073	0.055	0.039	0.145	0.039	0.043
DVBT	0.039	0.043	0.043	0.051	0.048	0.115	0.039	0.000	0.058
LTE 800 Uplink	0.027	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
LTE 800 Downlink	0.000	0.027	0.000	0.000	0.034	0.034	0.019	0.000	0.000
Uplink 900	0.000	0.000	0.000	0.000	0.000	0.000	0.113	0.238	0.064
Downlink 900	0.307	0.143	0.159	0.134	0.133	0.305	0.147	0.148	0.250
Uplink 1800	0.019	0.019	0.019	0.000	0.000	0.000	0.214	0.223	0.355
Downlink 1800	0.311	0.136	0.208	0.162	0.143	0.314	0.181	0.156	0.506
DECT	0.043	0.019	0.027	0.000	0.019	0.043	0.034	0.019	0.039
Uplink 1900	0.000	0.000	0.000	0.000	0.000	0.000	0.058	0.181	0.061
Downlink 2100	0.152	0.093	0.134	0.108	0.080	0.262	0.113	0.149	0.129
Wifi 2 GHz	0.019	0.000	0.000	0.000	0.000	0.000	0.000	0.027	0.019
Wifi 5Ghz	0.027	0.027	0.027	0.027	0.027	0.027	0.034	0.034	0.048
LTE 2600 Uplink	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
LTE 2600 Downlink	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000
Total RF-EMF	**0.473**	**0.230**	**0.324**	**0.255**	**0.228**	**0.528**	**0.393**	**0.461**	**0.692**

was observed between different city centers (minimum 0.36 V/m, median 0.427 V/m, maximum 0.674 V/m, and coefficient of variation 0.518). The pattern was similar for downlink whereas for uplink and broadcasting the coefficient of variation (CV) tended to be higher.

3.3. Repeatability RF-EMF exposure level

To assess the repeatability, we looked at the relationship between the first and the second measurements per microenvironment (mean of both paths combined). Spearman correlation between the first and the second measurements (arithmetic mean values) of all outdoor microenvironment was 0.89 for total RF-EMF, 0.90 for all five mobile phone downlink bands combined, 0.51 for all five uplink bands combined and 0.79 for broadcasting (Fig. 2). We also looked at Spearman correlation per type of microenvironment. The area specific correlations between first and second measurement for total RF-EMF were 0.50 for city centers, 0.86 for rural centers, 0.80 for central residential areas, 0.70 for non-central residential areas, 0.88 for rural residential areas and 1.0 for industrial areas. The correlations for downlink were 0.0 for city centers, 0.78 for rural centers, 0.60 for central residential areas, 0.40 for non-central residential areas, 0.94 for rural residential areas and 1.0 for industrial areas. The correlations for uplink were 0.70 for city centers, 0.14 for rural centers, 0.80 for central residential areas, −0.30 for non-central residential areas, 0.66 for rural residential areas and 1.0 for industrial areas. The correlations for broadcasting were 0.70 for city centers, 0.74 for rural centers, 0.80 for central residential areas, 0.90 for non-central residential areas, 0.86 for rural residential areas and 0.80 for industrial areas.

We further looked into repeatability of the measurements per path (instead of per microenvironment). Corresponding Spearman correlation coefficients were slightly lower except for uplink (0.83 for total RF-EMF and for all five mobile phone downlink bands combined, 0.54 for all five uplink bands combined and 0.79 for broadcasting) (Supplementary material: Fig. S1). We also looked into correlation per type of microenvironment for path 1 and path 2. The correlations for total RF-EMF were –0.14 for city centers, 0.70 for rural centers, 0.45 for central residential areas, 0.72 for non-central residential areas, 0.68 for rural residential areas and 0.65 for industrial areas. The correlations for downlink were –0.03 for city centers, 0.72 for rural centers, 0.27 for central residential areas, 0.75 for non-central residential areas, 0.69 for rural residential areas and 0.61 for industrial areas. The correlations for uplink were 0.50 for city centers, 0.38 for rural centers, 0.33 for

Table 2
Distribution and variability of area specific mean RF-EMF exposure levels (both paths combined per microenvironment) within the same type of microenvironment (all values are in V/m, except for the coefficient of variation CV).

Frequency band	Microenvironment	n	mean	Min	25perc	median	75perc	max	SD[a]	CV[b]
Total	City center	10	0.473	0.36	0.376	0.427	0.485	0.674	0.34	0.518
	Rural center	30	0.229	0.062	0.135	0.171	0.207	0.569	0.264	1.327
	Central residential area	9	0.323	0.112	0.214	0.32	0.402	0.454	0.263	0.661
	Non-central residential area	10	0.254	0.069	0.18	0.213	0.337	0.381	0.232	0.836
	Rural residential area	28	0.227	0.056	0.104	0.186	0.216	0.526	0.261	1.318
	Industrial area	10	0.527	0.213	0.336	0.57	0.615	0.745	0.416	0.624
Downlink	City center	10	0.463	0.357	0.362	0.41	0.48	0.669	0.342	0.545
	Rural center	30	0.219	0.033	0.114	0.136	0.203	0.568	0.266	1.485
	Central residential area	9	0.294	0.11	0.211	0.301	0.376	0.397	0.233	0.629
	Non-central residential area	10	0.237	0.06	0.148	0.209	0.304	0.363	0.218	0.846
	Rural residential area	28	0.214	0.038	0.092	0.151	0.196	0.523	0.262	1.497
	Industrial area	10	0.511	0.142	0.318	0.555	0.582	0.739	0.419	0.671
Uplink	City center	10	0.039	0.014	0.019	0.024	0.029	0.08	0.046	1.432
	Rural center	30	0.022	0.005	0.006	0.009	0.014	0.083	0.037	2.886
	Central residential area	9	0.023	0.008	0.009	0.019	0.03	0.042	0.024	1.079
	Non-central residential area	10	0.017	0.006	0.008	0.012	0.02	0.035	0.019	1.225
	Rural residential area	28	0.011	0.005	0.006	0.007	0.011	0.028	0.014	1.544
	Industrial area	10	0.012	0.005	0.008	0.011	0.015	0.018	0.01	0.724
Broadcasting	City center	10	0.075	0.015	0.02	0.028	0.05	0.164	0.1	1.8
	Rural center	30	0.059	0.012	0.021	0.031	0.062	0.143	0.075	1.614
	Central residential area	9	0.129	0.013	0.022	0.107	0.14	0.254	0.148	1.326
	Non-central residential area	10	0.088	0.021	0.027	0.043	0.121	0.164	0.097	1.217
	Rural residential area	28	0.071	0.013	0.024	0.034	0.064	0.207	0.096	1.86
	Industrial area	10	0.12	0.021	0.036	0.084	0.126	0.266	0.146	1.476

[a] Standard deviation.
[b] CV = SD/mean.

central residential areas, 0.55 for non-central residential areas, 0.63 for rural residential areas and 0.28 for industrial areas. The correlations for broadcasting were 0.83 for city centers, 0.90 for rural centers, 0.73 for central residential areas, 0.82 for non-central residential areas, 0.93 for rural residential areas and 0.81 for industrial areas.

On average, total RF-EMF exposure level of all mean values per microenvironment was 0.036 V/m higher in the first measurements compared to the second measurements (Table 3). The highest mean difference was observed for the city centers (0.124 V/m) followed by central residential areas (0.079 V/m) and the lowest in rural areas (0.001 V/m). Since downlink contributed the most to total exposure, the mean difference between first and second measurement found similar to total RF-EMF exposure. In case of uplink it was the other way around, levels were 0.007 V/m higher in the second measurements.

3.4. *Representativeness of RF-EMF exposure measurements on one path*

To evaluate the representativity of each path for a given microenvironment, we calculated the correlation between measurements from the first path with the measurements from the second path within each microenvironment. The Spearman correlation of arithmetic exposure between path 1 and path 2 was 0.75 for total RF-EMF, 0.76 for downlink, 0.55 for uplink and 0.85 for broadcasting (Fig. 3). Analyses based on geometric mean values per path instead of arithmetic mean values, yielded somewhat higher correlation coefficients 0.77 for total RF-EMF, 0.76 for downlink, 0.67 for uplink and 0.91 for broadcast.

3.5. *Expected precision of microenvironmental measurements*

Table S3 shows the expected precision of arithmetic mean values per microenvironment conducted for 30 min (path 1 and path 2 combined). For 5 city center measurements with a mean value for total RF-EMF of 0.473 V/m, the 95% confidence interval would be 0.35–0.57 V/m, for 10 city center measurements, the 95% confidence interval would be 0.39–0.55 V/m, for 20 city center measurements, the 95% confidence interval would be 0.41–0.53 V/m and for 40 city center measurements, the 95% confidence interval would be 0.43–0.51 V/m. Thus, with increasing number of measurements per microenvironment, the mean total RF-EMF exposure can be predicted with higher precision since the standard error decreases by 1/sqrt (number of measurements). If measurements were conducted for only 15 min instead of 30 min per microenvironment, the precision is only slightly reduced (Supplementary material: Table S4).

4. Discussion

This study analyzed the repeatability and representativity of RF-EMF exposure levels across 51 different outdoor microenvironments in Switzerland using portable exposimeters following a standardized measurement protocol. From this data we calculated expected the precision of mean exposure per type of microenvironment as a function of the number of measured microenvironments for planning of a future monitoring.

Our analyses within microenvironments found that the total RF-EMF and downlink was highest in industrial areas and city centers. For residential areas, we found a gradient with respect to urbanization: the more urban an area, the higher total RF-EMF and downlink exposure. At outdoor location uplink and WLAN were mostly negligible but uplink was a relevant contributor in public transports. For repeated measurements, we found a strong correlation for total RF-EMF and downlink (0.90), whereas variability within the area was somewhat larger (correlation between the first path and the second path measurement; 0.65 for total RF-EMF and downlink).

4.1. *Strength and limitation*

Measurements in different microenvironments were done using the same protocol which allows direct comparison of the measurements. The exposimeter was kept on the top of a backpack

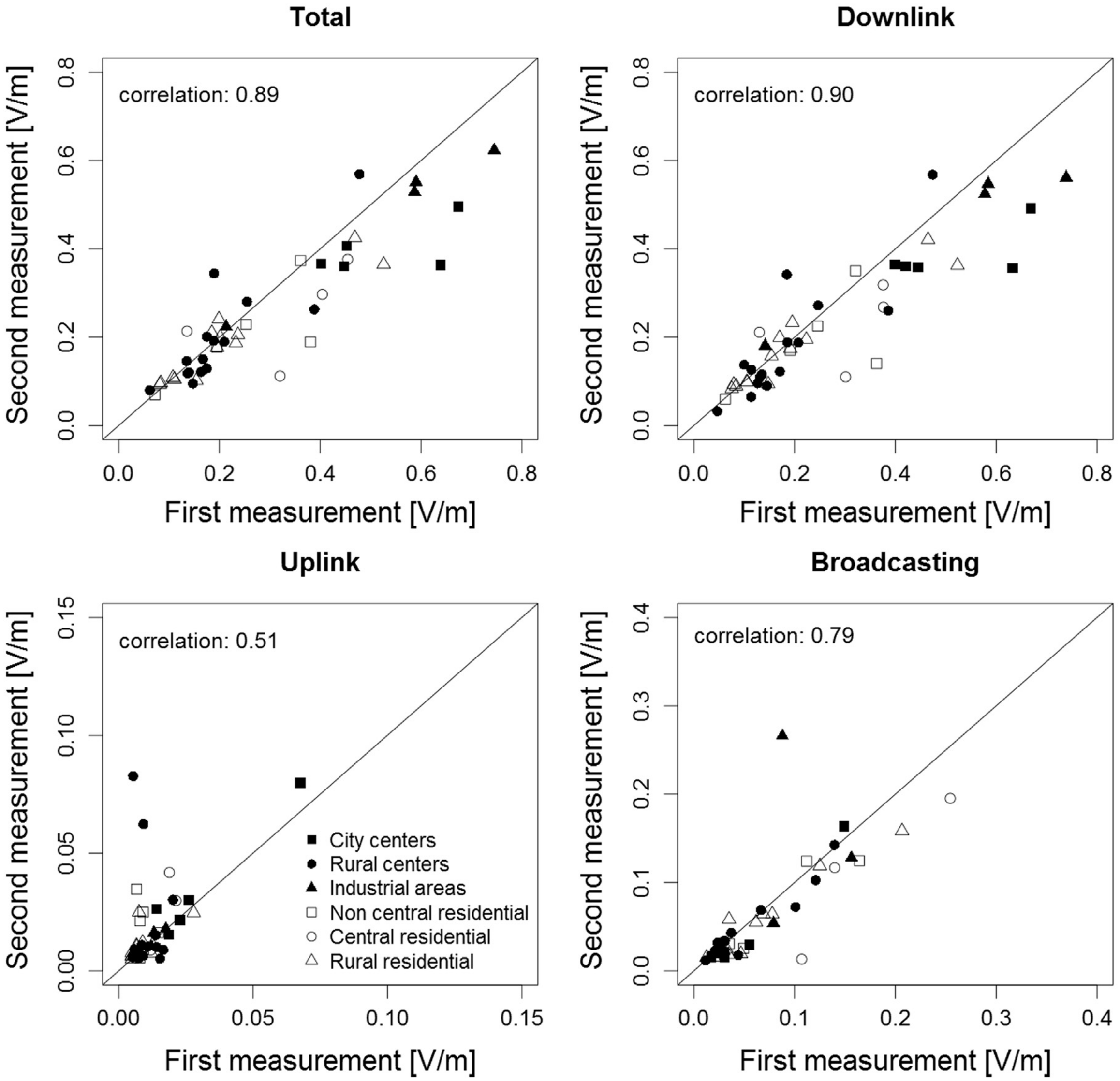

Fig. 2. Comparison of the ***area-specific*** arithmetic mean of total RF-EMF, downlink, uplink and broadcasting exposure between the first and second measurement in the different microenvironments in Switzerland including Spearman correlation coefficient.

at a distance of about 20–30 cm from the body slightly above the height of the head in order to minimize body shielding. While traveling by public transport, the backpack was either carried by the study assistant or was kept vertical on the seat of the public transport to ensure minimum shielding. Previous studies have shown that keeping the device close within 10–50 mm of the body produces underestimation of the incident field strength of approximately 10 to 50% for different RF-EMF bands (Blas et al., 2007; Bolte and Eikelboom, 2012; Iskra et al., 2010; Knafl et al., 2008; Neubauer et al., 2007; Radon et al., 2006). Since the study assistant turned off his own mobile phone one can clearly attribute the measured uplink to the emissions from other people's mobile phones. Such an attribution is tricky in personal measurements studies, where volunteers may not be willing to turn off their mobile phone (Frei et al., 2009b; Viel et al., 2009).

In this study most of the repeated measurements in the same microenvironments were conducted by two different study assistants. This strategy has both pros and cons. An analysis of the GPS recorded coordinates showed that the study assistants did not always follow exactly the same path. Thus, our observed repeatability may be somewhat lower than in a study where all repeated measurements are taken by the same study assistant like in Amsterdam, Basel, Brussels, and Ghent (Urbinello et al., 2014a). However, such a situation with different study assistants conducting measurements may be more representative for a monitoring study, where not always exactly the same person can do the measurements over a longer time period.

In general, repeatability for area averages based on measurement distance of about 1 km that took about 15 min to cover by foot was high for total RF-EMF (0.89), downlink (0.90) and broadcasting (0.79) but, as expected, somewhat lower for uplink (0.51). There are some differences between repeatability for different types of area. For instance, for city centers correlation is 0.5 for total RF-EMF and even only 0.0 for downlink. This is because of the small variability of exposure within this type of area. Thus, small changes in the absolute value have substantial effects on the correlation coefficients. Further, the number of repeated measurements is small for some areas and correlation coefficients should thus not be over weighted.

4.2. Comparison of exposure level with existing studies

The variability of mean total RF-EMF exposure levels in our study were in accordance with previous studies. We found mean

Table 3
Distribution of differences between first and second measurements per outdoor microenvironment (both areas combined) for RF-EMF exposure for total, uplink, downlink and broadcasting (all values are in V/m).

Frequency band	Microenvironment	n	avg. Difference	min	25perc	median	75perc	Max	SD
Total	All	46	0.036	−0.155	−0.011	0.020	0.053	0.275	0.079
	City center	5	0.124	0.035	0.046	0.087	0.178	0.275	0.101
	Rural center	15	0.001	−0.155	−0.022	0.017	0.031	0.125	0.064
	Central residential area	4	0.079	−0.079	0.039	0.093	0.132	0.208	0.119
	Non-central residential area	5	0.045	−0.012	0.003	0.018	0.024	0.192	0.083
	Rural residential area	13	0.022	−0.042	−0.012	0.007	0.044	0.176	0.055
	Industrial area	4	0.052	−0.011	0.026	0.048	0.074	0.122	0.055
Downlink	All	46	0.037	−0.157	−0.004	0.020	0.054	0.276	0.082
	City center	5	0.126	0.035	0.057	0.086	0.177	0.276	0.099
	Rural center	15	0.004	−0.157	−0.015	0.019	0.040	0.125	0.066
	Central residential area	4	0.069	−0.081	0.023	0.083	0.129	0.191	0.114
	Non central residential area	5	0.047	−0.030	0.003	0.020	0.021	0.222	0.100
	Rural residential area	13	0.020	−0.042	−0.008	0.006	0.028	0.176	0.053
	Industrial area	4	0.058	−0.039	0.017	0.045	0.085	0.180	0.091
Uplink	All	46	−0.007	−0.077	−0.012	−0.001	0.002	0.016	0.016
	City center	5	−0.005	−0.012	−0.011	−0.004	0.001	0.003	0.007
	Rural center	15	−0.009	−0.077	−0.006	0.000	0.004	0.010	0.024
	Central residential area	4	−0.007	−0.023	−0.012	−0.003	0.002	0.003	0.012
	Non central residential area	5	−0.011	−0.029	−0.016	−0.013	−0.001	0.003	0.013
	Rural residential area	13	−0.004	−0.031	−0.004	−0.002	0.001	0.016	0.012
	Industrial area	4	−0.005	−0.022	−0.006	0.000	0.000	0.002	0.011
Broadcasting	All	46	0.007	−0.178	−0.002	0.006	0.022	0.097	0.035
	City center	5	0.006	−0.015	0.000	0.002	0.017	0.026	0.016
	Rural center	15	0.005	−0.008	−0.002	0.001	0.010	0.029	0.011
	Central residential area	4	0.046	0.005	0.019	0.041	0.069	0.097	0.040
	Non central residential area	5	0.012	−0.012	0.003	0.004	0.024	0.040	0.020
	Rural residential area	13	0.009	−0.024	0.005	0.007	0.014	0.048	0.017
	Industrial area	4	−0.031	−0.178	−0.045	0.012	0.026	0.029	0.099

total RF-EMF exposure of 0.34 V/m in all microenvironments combined which has been consistent with mean total RF-EMF exposure of 0.28 V/m in outdoors in Basel (Frei et al., 2009a, 2009b). Our microenvironment specific mean total RF-EMF exposure values are in the same range as reported by other studies: 0.216 V/m in urban outdoor environment based on surrogate modeling and sequential design (Aerts et al., 2013a), 0.201 V/m in all microenvironments combined in France (Viel et al., 2009), 0.49 V/m in urban outdoor in Belgium (Aerts et al., 2013b) and 0.51 V/m in outdoor unspecified in Belgium, The Netherlands and Sweden (Joseph et al., 2012).

In terms of differences between types of outdoor microenvironments, we found the highest total mean RF-EMF exposure levels in industrial areas (0.53 V/m) and city centers (0.47 V/m). The latter was also seen in Urbinello et al., (2014a), who reported the total RF-EMF exposure levels between 0.30 and 0.53 V/m for various downtown and business areas in four different types of urban areas in the cities of Basel and Amsterdam. Our survey identified downlink as the prominent contributor in outdoor microenvironments (>80%) and absolute contributions were the highest in industrial areas (0.51 V/m) and city centers (0.46 V/m). The mean downlink exposure ranged from 0.21 V/m to 0.51 V/m for all outdoor microenvironments combined in our study which was similar to Basel (0.22 V/m) and Amsterdam (0.41 V/m) all outdoor combined (Urbinello et al., 2014c). Joseph et al. in a personal RF-EMF measurement study also found similar downlink exposure levels in urban outdoor areas in Ghent and Brussels; 0.52 V/m from downlink exposure in Ghent and Brussels in urban outdoor areas (2008).

In our outdoor microenvironments, exposure from uplink was significantly lower than downlink exposure values in all microenvironments which is in line with previous microenvironmental measurement studies (Estenberg and Augustsson, 2014; Urbinello et al., 2014b, 2014c). Our microenvironmental measurements cannot directly be compared with volunteer studies, since in our case the mobile phone of the person carrying the measurement device is turned off. Hence the uplink exposure only represents exposure from environmental sources. This is mostly not the case for volunteer studies and thus such studies record higher proportion of uplink (Frei et al., 2009b; Bolte and Eikelboom, 2012). Although most of these studies used strategies to remove measurements during own calls from the analyses, one still expects some influences from the own mobile phone due to missed calls or due to stand-by traffic (Urbinello and Röösli, 2013). In our study, uplink was more relevant for public transport with the highest values in trains and trams (0.37 V/m) followed by bus (0.25 V/m). Exposure to uplink depends mainly upon the number of active mobile phones in proximity of the measurement devices. In our measurement, the uplink exposure values in public transports were lower than uplink exposure values in train in Basel (0.97 V/m), Ghent (0.83 V/m) and Brussels (1.05 V/m) (Urbinello et al., 2014b). This could be due to the fact that our survey considered public transports from rural, semi-urban and urban combined while Basel, Ghent and Brussels are three bigger cities, and hence public transport may be more crowded and a higher uplink could be expected. In addition, we used public transport to travel from one area to another. Thus, our measurements are not restricted to rush hour and may roughly represent a working hour daytime average. Whereas the absolute contribution of uplink was relatively similar between the three modes of public transport we found striking differences for downlink exposure. The substantial higher downlink exposure in trams may be explained by high base station density in the very central part of the cities, where trams are running as well as microcells operating often at tram stations.

4.3. Implications for future microenvironmental monitoring studies

This microenvironmental survey showed mobile phone base stations as the main contributors of RF-EMF in all selected

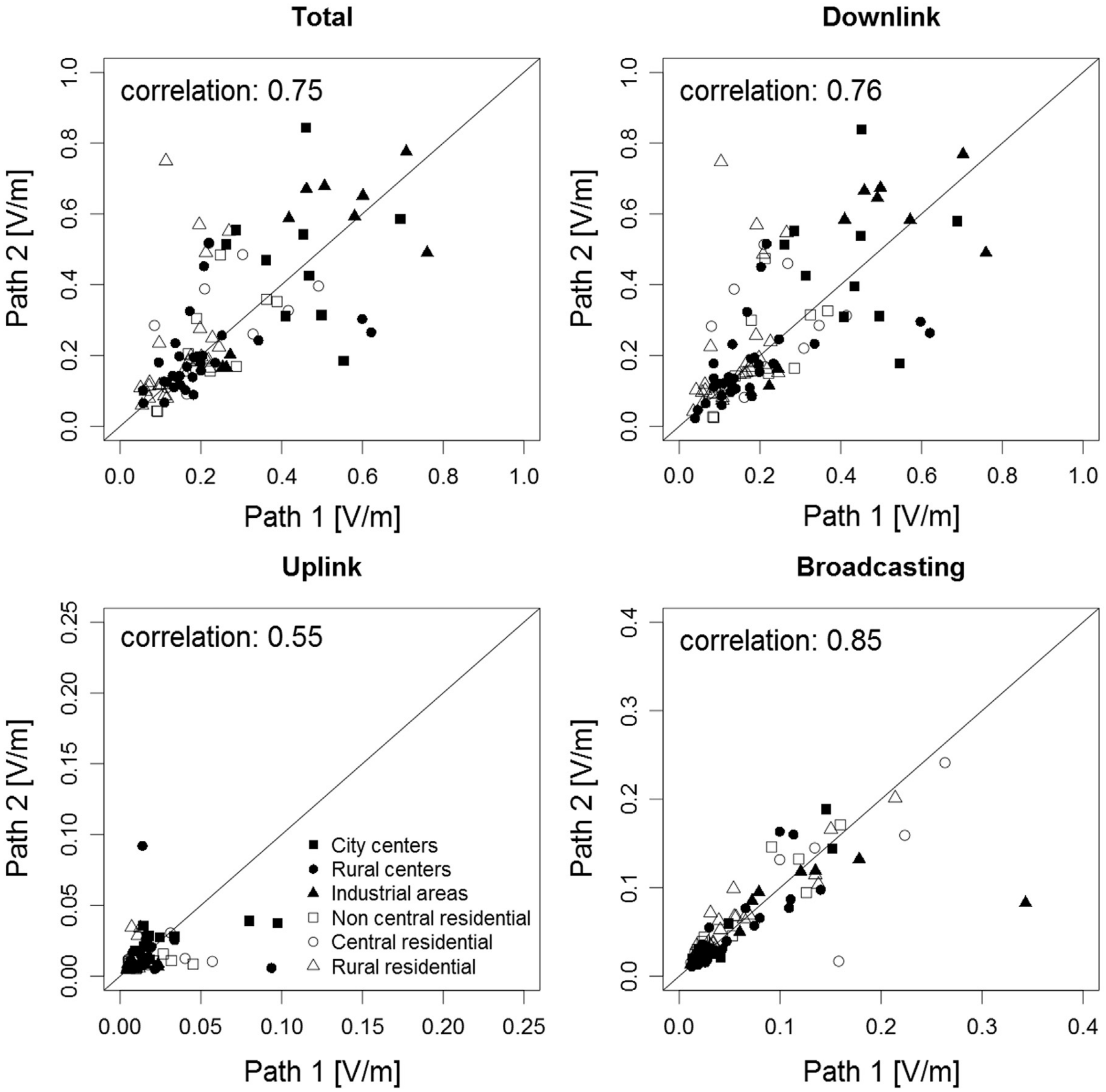

Fig. 3. Comparison of arithmetical mean of total RF-EMF, downlink, uplink and broadcasting exposure between the path 1 and path 2 measurement taken on the same day within the same microenvironment.

microenvironments. By using 5–15 different areas per type of microenvironment we could observe clear differences in the RF-EMF exposure between different types of microenvironments. For instance, relatively high downlink exposure in industrial areas and low exposure in residential areas reflects the policy in Switzerland to place mobile phone base station outside residential areas as much as possible. Obviously, with increasing urbanization this becomes more difficult and this may explain the higher downlink exposure in urban residential areas. Our study demonstrates that such microenvironmental measurements are useful to characterize and monitor the exposure situation in the everyday environment. Obviously the approach is mainly feasible in areas, which are accessible by the public. For private places or in homes, where contact with the inhabitants are needed, other methods might be more feasible.

In the context of a monitoring, the main aim would be to obtain representative exposure values for a specific type of microenvironments. This would then allow comparing exposure values between different types of microenvironments, comparing exposure levels in the same type of microenvironment between different areas (e.g. countries) or to analyze trends in exposure over time for different microenvironments. A crucial question when planning such a monitoring would then be the measurements duration per area including the selection of the measurement places and the number of microenvironments that have to be measured to obtain the typical exposure situation for a specific type of microenvironment. To evaluate these factors, we have defined two paths per microenvironment and compared the exposure between the two paths. We could see that the repeatability was not strongly affected by the measurement duration (Supplementary material: Table S3 and Table S4). For mean values based on two paths (approx. 30 min) correlation between the first and second measurement was 0.89 for total exposure whereas only slightly lower (0.83) mean values per path (approx. 15 min) were considered. A similar picture was observed for the predicted precision of total RF-EMF mean values per type of microenvironment. For instance, for 30 min mean value, mean predicted exposure in city centers was 0.47 V/m and the predicted 95% confidence interval ranged from 0.41 to 0.53 V/m for 20 microenvironments, which is clearly different from the mean exposure values observed in different types of residential areas < 0.33. The same calculation based on 15 min mean yielded a mean exposure of 0.46 V/m for city centers and the predicted 95% confidence interval ranged from 0.40 to 0.52 V/m for 20 microenvironments.

5. Conclusion

This study demonstrates that microenvironmental surveys yield highly reproducible measurements of relevant RF-EMF sources in the everyday environment. Collecting data by trained study assistants on a measurement path of about 1 km in length resulting in about 225 measurements points per area provide an average exposure which is roughly representative for the specific microenvironment. Nevertheless we found relatively high variability between different microenvironments from the same type. Thus, about 10-20 different microenvironments of the same type needs to be measured in the framework of a monitoring aiming at comparing exposure values between different types of microenvironments and to evaluate long term temporal trends in the exposure situation.

Conflict of interest

The authors declare no conflict of interest.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.envres.2016.06.020.

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SUPPLEMENTAL MATERIAL

Table of Contents

Table S1: List of Municipalities and microenvironments

Muncipalities	Communty typology ARE	Microenviroments					
		City center	Rural center	Rural residential area	Central residential area	Non-central residential area	Industrial area
Nesslau-Neu St. Johann	Agricultural community		✔	✔			
Lungern	Agricultural community		✔	✔			
Zürich	Big center	✔			✔	✔	✔
Lugano	Big center	✔			✔	✔	
Lausanne	Big center			✔	✔	✔	
Rümlang	Crown big center		✔	✔			✔
St-Blaise	Crown medium center		✔	✔			
Gränichen	Crown medium center		✔	✔			
Neuchatel	Medium center	✔			✔	✔	
Aarau	Medium center	✔			✔	✔	✔
Seewen	Periurban rural community		✔	✔			
Frick	Periurban rural community		✔	✔			✔
Pully	Secondary center of big center		✔	✔			
Münchenstein	Secondary center of big center		✔	✔			
Dübendorf	Secondary center of big center		✔	✔			✔
Bioggio	Secondary center of big center		✔	✔			
Zweisimmen	Small center		✔	✔			
Watwil	Small center		✔	✔			✔
Brienz	Tourist community		✔	✔			
Gstaad (Saanen)	Tourist community		✔	✔			

Table S2: Overview of frequency bands and measuring range of ExpoM-RF

Frequency bands	**Frequency range**	**Dynamic range**	
FM Radio	87.5 – 108 MHz	0.02 V/m	5 V/m
DVB-T	470 – 790 MHz	0.005 V/m	5 V/m
Mobile 800 MHz downlink	791 – 821 MHz	0.005 V/m	5 V/m
Mobile 800 MHz uplink	832 – 862 MHz	0.005 V/m	5 V/m
Mobile 900 MHz uplink	880 – 915 MHz	0.005 V/m	5 V/m
Mobile 900 MHz downlink	925 – 960 MHz	0.005 V/m	5 V/m
Mobile 1800 MHz uplink	1710 – 1785 MHz	0.005 V/m	5 V/m
Mobile 1800 MHz downlink	1805 – 1880 MHz	0.005 V/m	5 V/m
DECT	1880 – 1900 MHz	0.005 V/m	5 V/m
Mobile 2.1 GHz uplink	1920 – 1980 MHz	0.003 V/m	5 V/m
Mobile 2.1 GHz downlink	2110 – 2170 MHz	0.003 V/m	5 V/m
ISM 2.4 GHz	2400 – 2485 MHz	0.005 V/m	5 V/m
Mobile 2.6 GHz uplink	2500 – 2570 MHz	0.003 V/m	5 V/m
Mobile 2.6 GHz downlink	2620 – 2690 MHz	0.003 V/m	5 V/m
Mobile 3.5 GHz	3400 – 3600 MHz	0.003 V/m	3 V/m
ISM 5.8 GHz / U-NII 1-2e	5150 – 5875 MHz	0.05 V/m	5 V/m

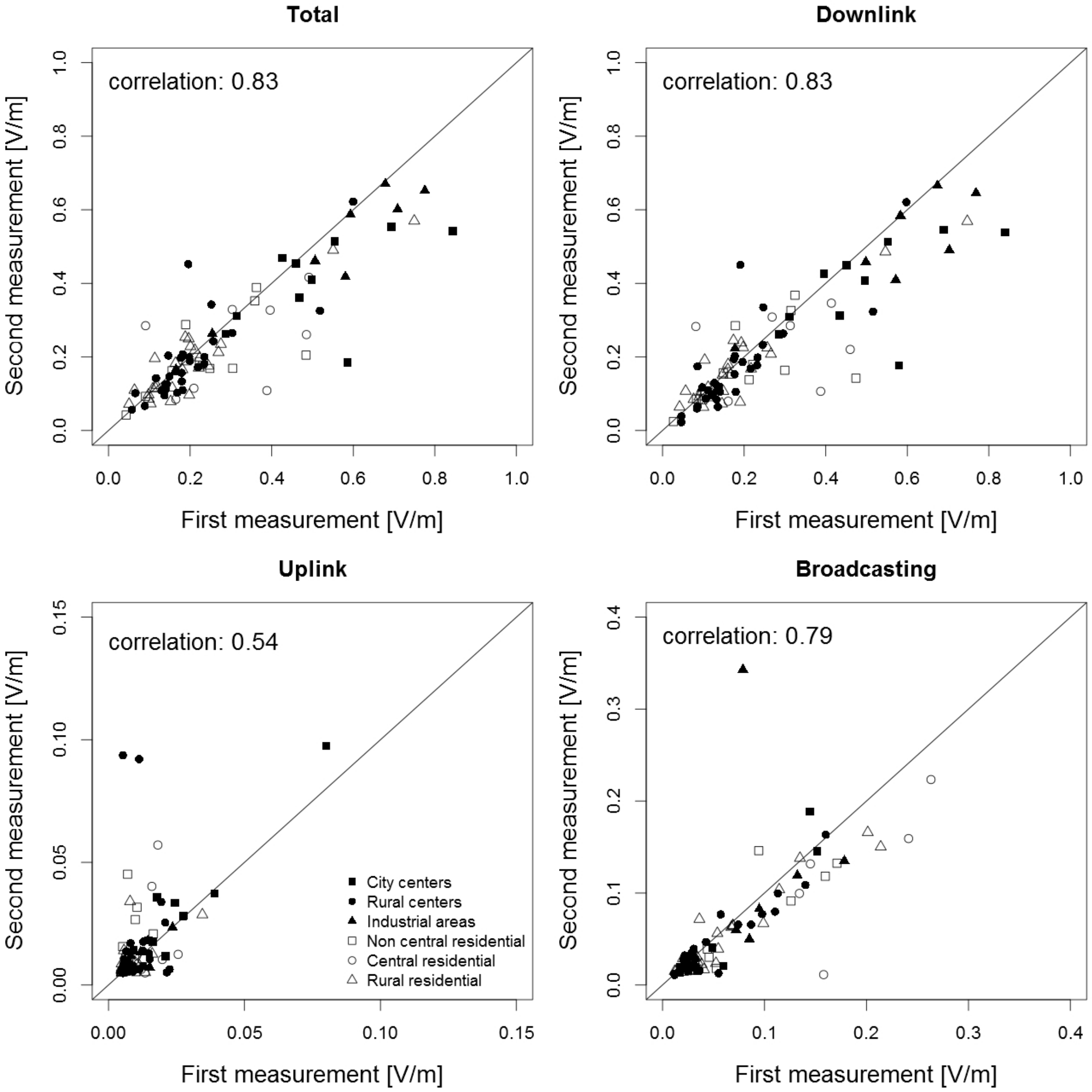
Table S3: Expected precision of mean arithmetic values per type of microenvironment for different sample sizes for 30 minutes (path1 and path2) (sd = standard deviation, CI = confidence interval, n= number of microenvironments, all values are in V/m)

band	area	mean	mean-sd	mean+sd	n=5		n=10		n=20		n=40	
					95% CI		95% CI		95% CI		95% CI	
Total	City Center	0.47	0.33	0.58	0.35	0.57	0.39	0.55	0.41	0.53	0.43	0.51
Total	Rural Center	0.23	<0	0.35	<0	0.34	0.09	0.31	0.15	0.29	0.18	0.27
Total	Central Residential Area	0.32	0.19	0.42	0.21	0.41	0.25	0.39	0.27	0.37	0.29	0.36
Total	Non-Central Residential Area	0.25	0.10	0.34	0.13	0.34	0.17	0.31	0.20	0.30	0.22	0.29
Total	Rural Residential Area	0.23	<0	0.35	<0	0.34	0.09	0.31	0.15	0.29	0.17	0.27
Total	Industrial Area	0.53	0.32	0.67	0.35	0.66	0.41	0.62	0.45	0.60	0.47	0.58
Downlink	City Center	0.46	0.31	0.58	0.33	0.56	0.38	0.54	0.40	0.52	0.42	0.50
Downlink	Rural Center	0.22	<0	0.35	<0	0.33	0.05	0.30	0.13	0.28	0.16	0.27
Downlink	Central Residential Area	0.29	0.18	0.38	0.19	0.37	0.23	0.35	0.25	0.33	0.26	0.32
Downlink	Non-Central Residential Area	0.24	0.09	0.32	0.12	0.31	0.16	0.29	0.19	0.28	0.20	0.27
Downlink	Village Residential Area	0.21	<0	0.34	<0	0.33	0.05	0.30	0.12	0.28	0.16	0.26
Downlink	Industrial Area	0.51	0.29	0.66	0.32	0.65	0.39	0.61	0.43	0.58	0.45	0.56
Uplink	City Center	0.04	<0	0.06	<0	0.06	0.01	0.05	0.02	0.05	0.03	0.05
Uplink	Rural Center	0.02	<0	0.04	<0	0.04	<0	0.04	<0	0.03	0.01	0.03
Uplink	Central Residential Area	0.02	<0	0.03	0.00	0.03	0.01	0.03	0.02	0.03	0.02	0.03
Uplink	Non-Central Residential Area	0.02	<0	0.03	<0	0.03	0.01	0.02	0.01	0.02	0.01	0.02
Uplink	Rural Residential Area	0.01	<0	0.02	<0	0.02	0.00	0.02	0.01	0.02	0.01	0.01
Uplink	Industrial Area	0.01	0.01	0.02	0.01	0.02	0.01	0.02	0.01	0.01	0.01	0.01
Broadcasting	City Center	0.08	<0	0.13	<0	0.12	<0	0.11	0.03	0.10	0.05	0.09
Broadcasting	Rural Center	0.06	<0	0.10	<0	0.09	<0	0.08	0.03	0.08	0.04	0.07
Broadcasting	Central Residential Area	0.13	<0	0.20	<0	0.19	0.05	0.18	0.08	0.16	0.10	0.15
Broadcasting	Non-Central Residential Area	0.09	<0	0.13	<0	0.13	0.04	0.12	0.06	0.11	0.07	0.10
Broadcasting	Rural Residential Area	0.07	<0	0.12	<0	0.12	<0	0.10	0.03	0.10	0.05	0.09
Broadcasting	Industrial Area	0.12	<0	0.19	<0	0.18	0.03	0.17	0.07	0.16	0.09	0.15

Table S4: Expected precision of mean arithmetic values per type of microenvironment for different sample sizes for 15 minutes (path2 only) (sd = standard deviation, CI = confidence interval, n= number of microenvironments, all values are in V/m)

band	area	mean	mean-sd	mean+sd	n=5		n=10		n=20		n=40	
					95% CI		95% CI		95% CI		95% CI	
Total	City Center	0.46	0.30	0.58	0.33	0.57	0.37	0.54	0.40	0.52	0.42	0.50
Total	Rural Center	0.23	<0	0.38	<0	0.37	<0	0.33	0.12	0.31	0.16	0.29
Total	Central Residential Area	0.29	0.07	0.40	0.11	0.39	0.18	0.37	0.22	0.35	0.24	0.33
Total	Non-Central Residential Area	0.24	0.10	0.33	0.13	0.32	0.17	0.30	0.19	0.29	0.21	0.27
Total	Rural Residential Area	0.17	0.08	0.22	0.09	0.22	0.12	0.20	0.14	0.19	0.15	0.19
Total	Industrial Area	0.51	0.29	0.67	0.32	0.65	0.39	0.62	0.43	0.59	0.45	0.57
Downlink	City Center	0.45	0.29	0.57	0.31	0.56	0.36	0.53	0.39	0.51	0.41	0.49
Downlink	Rural Center	0.22	<0	0.37	<0	0.36	<0	0.33	0.09	0.30	0.14	0.28
Downlink	Central Residential Area	0.25	0.08	0.35	0.11	0.34	0.17	0.31	0.19	0.30	0.21	0.28
Downlink	Non-Central Residential Area	0.23	0.09	0.31	0.11	0.30	0.16	0.28	0.18	0.27	0.19	0.26
Downlink	Rural Residential Area	0.15	0.05	0.20	0.07	0.20	0.10	0.19	0.12	0.18	0.13	0.17
Downlink	Industrial Area	0.49	0.24	0.65	0.28	0.64	0.35	0.60	0.40	0.57	0.43	0.55
Uplink	City Center	0.04	<0	0.07	<0	0.07	<0	0.06	0.02	0.06	0.03	0.05
Uplink	Rural Center	0.02	<0	0.05	<0	0.04	<0	0.04	<0	0.03	<0	0.03
Uplink	Central Residential Area	0.03	<0	0.04	<0	0.04	0.01	0.04	0.02	0.04	0.02	0.03
Uplink	Non-Central Residential Area	0.02	<0	0.03	<0	0.03	0.01	0.03	0.01	0.03	0.02	0.03
Uplink	Rural Residential Area	0.01	0.00	0.01	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Uplink	Industrial Area	0.02	0.00	0.02	0.01	0.02	0.01	0.02	0.01	0.02	0.01	0.02
Broadcasting	City Center	0.07	<0	0.12	<0	0.12	<0	0.10	0.03	0.10	0.05	0.09
Broadcasting	Rural Center	0.06	<0	0.09	<0	0.09	0.01	0.08	0.03	0.07	0.04	0.07
Broadcasting	Central Residential Area	0.14	<0	0.21	<0	0.20	0.06	0.19	0.09	0.18	0.11	0.17
Broadcasting	Non-Central Residential Area	0.08	<0	0.13	<0	0.12	0.04	0.11	0.06	0.10	0.06	0.10
Broadcasting	Rural Residential Area	0.07	<0	0.12	<0	0.12	<0	0.11	0.02	0.10	0.04	0.09
Broadcasting	Industrial Area	0.14	<0	0.24	<0	0.23	<0	0.21	0.06	0.19	0.09	0.18

Figure S1: Comparison of the *path-specific* arithmetic mean of total RF-EMF, downlink, uplink and broadcasting exposure between the first and second measurement in the different microenvironments in Switzerland including Spearman correlation coefficient



4.3.Article 3: Comparison of radiofrequency electromagnetic field exposure levels in different everyday microenvironments in an international context

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Comparison of Radiofrequency Electromagnetic Field Exposure levels in different Everyday Microenvironments in an International context

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Abstract

Background: The aim of this study was to quantify RF-EMF exposure applying a tested protocol of RF-EMF exposure measurements using portable devices with a high sampling rate in different microenvironments of Switzerland, Ethiopia, Nepal, South Africa, Australia and the United States of America.

Method: We used portable measurement devices for assessing RF-EMF exposure in 94 outdoor microenvironments and 18 public transport vehicles. The measurements were taken either by walking with a back pack, with the devices at the height of and a distance of 20-30 cm from the head, or driving a car with the devices mounted on its roof, which was 170-180 cm above the ground. The measurements were taken for about 30 minutes while walking and about 15-20 minutes while driving in each microenvironment, with a sampling rate of once every 4 seconds (ExpoM-RF) and 5 seconds (EME Spy 201).

Results: Mean total RF-EMF exposure in various outdoor microenvironments varied between 0.23 V/m (non-central residential area in Switzerland) and 1.85 V/m (university area in Australia), and across modes of public transport between 0.32 V/m (bus in rural area in Switzerland) and 0.86 V/m (Auto rickshaw in urban area in Nepal). For outdoor areas the major exposure contribution was from mobile phone base stations, which contributed in all measured outdoor microenvironments at least 65%. Uplink from mobile phone handsets was generally very small, except in Swiss trains and some Swiss buses.

Conclusions: This study demonstrates high RF-EMF variability between the 94 selected microenvironments from all over the world. Exposure levels tended to increase with increasing urbanity. In most microenvironments downlink from mobile phone base stations are the most relevant contributors.

KEY WORDS: Radio-frequency electromagnetic fields (RF-EMF); Microenvironment; Uplink; Downlink; Exposure assessment; Mobile phone handset; Mobile phone base station

1. Introduction

Good knowledge of the radiofrequency electromagnetic field (RF-EMF) exposure of the population is useful for risk communication, assessment and management (Dürrenberger et., al 2014). However, little is known about differences in RF-EMF exposure of the general public in various microenvironments in different parts of the world. Although recent studies have quantified RF-EMF levels in different microenvironments in Europe (Blas et a., 2007; Bolte & Eikelboom, 2012; Frei et al., 2009; Iskra et al., 2010; Joseph et al., 2010; Knafl et al., 2008; Sagar et al., 2017, 2016; Urbinello et al., 2014a, 2014b, 2014c; Viel et al., 2009), the rest of the world still remains untouched. Further, the available European studies used different measurement approaches and different kinds of measurement devices, which substantially hamper comparability (Sagar et al., 2017). Thus, a comparative RF-EMF measurement using a standard protocol across several countries across the globe would be highly informative and enhance our knowledge of the populations' exposure situation on a global scale. Hence this study continues the effort of Sagar et al., 2016, where a measurement procedure was developed for Switzerland to monitor RF-EMF exposure in publicly accessible microenvironments, with the aim to quantify the exposure levels in various microenvironments in Switzerland, Ethiopia, Nepal, South Africa, Australia and the United States of America.

2. Measurements and Methods

2.1 Microenvironments selection

Table S1 (Supplementary material: Table S1) provides the overview of the selected microenvironments with a schedule of their measurements across all the six countries. We selected 94 matched microenvironments, from six countries across the globe, following the tested protocol in Switzerland (Sagar et al., 2016). The 94 selected microenvironments comprised of 15 matched microenvironments from Switzerland (Europe), 18 from Ethiopia (Africa), 12 from Nepal (Asia), 17 from South Africa (Africa), 24 from Australia (Australia) and 8 from the United State of America (North America). Our selection of microenvironments represents urban and rural areas across the six countries where people spend significant amount of time, similar to some previous studies: city centers, central residential, non-central residential, rural centers, rural residential, industrial, tourist and university areas(Bhatt et al., 2016a, 2016b; Bolte & Eikelboom, 2012; Frei et al., 2009; Joseph et al., 2010; Röösli et al., 2010; Sagar et al., 2016; Urbinello et al., 2014a, 2014b). In addition to the 94 microenvironments across six countries, 18 measurements were also conducted in public transportation (train, tram, bus, taxi, auto rickshaw) during the journey of the study assistant to and from the measurement areas on the day of measurement.

2.2 Measuring devices

The RF-EMF exposure measurements in all the selected international microenvironments were measured using three different kinds of portable RF meter; the “ExpoM-RF v1”, “ExpoM-RF v3” and “EME Spy 201”. The two versions of ExpoM-RF (version 1: Expom and version 3: ExpoM-RF) were developed by Fields At Work (http://www.fieldsatwork.ch) and the EME Spy 201 was developed by Microwave Vision Group, France (http://www.mvg-world.com/en). The frequency bands of the ExpoM-RF covers the frequencies of most public RF-EMF emitting devices currently used in

Switzerland, Ethiopia, Nepal, South Africa and Australia while the frequency bands of the EME Spy 201 cover the frequencies of most public RF-EMF emitting devices currently used in the United States of America (Supplementary material: Table S2). The upper limit of the ExpoM-RF dynamic range is 5 V/m for all frequency bands, and the lower limit of the dynamic range varies for different frequency bands; between 0.003 and 0.05 V/m. The upper detection limit of the EME Spy 201 is 6 V/m and the lower detection limit is 0.005 V/m, except for FM, TV-VHF and Wifi 5G, where it was 0.015 V/m. Both the portable devices record values below the lower detection limit, but we censored the values below half of the lower detection limit to half of the lower quantification limit. Similarly, all high values were censored at 5 V/m to prevent bias between measurements taken with different devices.

2.3 Measurement procedure

The RF-EMF exposure measurements were conducted either by walking (Switzerland and Nepal) or driving a car with the ExpoM-RF device mounted on its roof (United States of America) or a mixture of walking and driving (Ethiopia, South Africa, and Australia) (Supplementary material: Table S1). Measurements by walking were conducted using a backpack with the device on its top, about 20-30 cm away from the body to ensure minimum shielding and measurements by driving a car were conducted with the devices mounted on its roof, which was 170-180 cm above the ground. The measurements in public transportation were conducted with either carrying the backpack by the study assistant or keeping it vertical on the seat of the public transportation. Personal mobile phones were switched off while taking the measurements, and a mobile phone with a time stamp app was used in flight mode to record the start and end times of each measurement while walking or driving.

Each of the selected 94 microenvironments in 6 countries was measured twice between 10 March 2015 and 14 April 2017 (details see Supplementary material: Table S1). The RF-EMF exposure measurements using the ExpoM-RF were taken with a sampling rate of once every 4 seconds, and the EME Spy 201 with a sampling rate of once every 5 seconds. All measurements were taken during daylight between 9am and 6pm in the respective countries, except the United States of America where we also took night time exposure measurements between 7pm and 9pm.

2.4 Statistical analyses

We considered five main groups of bands: downlink (exposure from mobile phone base stations), uplink (exposure from mobile phone handsets), broadcasting (exposure from FM radio and TV), other (WiFi 2G) and total RF-EMF (sum of downlink, uplink, broadcasting and other) for individual frequency bands used in the respective countries (Supplementary material: Table S3). We descriptively analyzed the exposure levels including arithmetic mean values for all outdoor exposure including public transport. To assess reliability of the exposure values, we used Spearman measure of association across first and second measurement, and across day and night time measurements. All the analyses were conducted using statistical software R version 3.1.3 3.1.3 (https://www.rproject.org/) and measured values were converted to power flux density (mW/m^2). We further assessed variability across various outdoor microenvironments among all the selected countries.

3. Results

3.1 Characteristics of RF-EMF exposure levels in various microenvironments across six countries

Figure 1 shows a box plot for total RF-EMF, downlink, uplink and broadcasting exposure, for eight different types of microenvironments across the six selected countries. The average exposure varied widely across the microenvironments. Figure 2 summarizes mean RF-EMF exposure levels across six countries for total RF-EMF, uplink, downlink, broadcasting and WiFi 2G, for each of the six different microenvironments. Mean total RF-EMF exposure for city centers was 0.48 V/m in Switzerland, 1.21 V/m in Ethiopia, 0.75 V/m in Nepal, 0.85 V/m in South Africa, 1.46 V/m in Australia and 1.24 V/m in the United States of America. Corresponding downlink exposure was 0.47 V/m, 0.94 V/m, 0.70 V/m, 0.81 V/m, 0.81 V/m and 1.22 V/m in Switzerland, Ethiopia, Nepal, South Africa, Australia and the United States respectively. Exposure from uplink was negligible in outdoor microenvironments, but broadcasting was relevant in Addis Ababa (Ethiopia), Sydney and Canberra (Australia): 1.18 V/m, 1.12 V/m and 1.76 V/m respectively. As a consequence, the highest total RF-EMF exposure levels measured in these microenvironments were 1.65 V/m, 1.80 V/m and 1.90 V/m respectively (Figure 3).

Mean total RF-EMF exposure for central residential areas was 0.35 V/m in Switzerland, 0.88 V/m in Ethiopia, 0.47 V/m in Nepal, 0.58 V/m in South Africa, 1.06 V/m in Australia and 1.44 V/m in the United States of America. Corresponding downlink exposure was 0.34 V/m, 0.67 V/m, 0.36 V/m, 0.55 V/m, 0.35 V/m and 1.39 V/m in Switzerland, Ethiopia, Nepal, South Africa, Australia and the United States respectively. Mean total RF-EMF exposure for industrial areas was 0.69 V/m in Switzerland, 0.36 V/m in Ethiopia, 0.31 V/m in Nepal, 0.92 V/m in South Africa, 0.32 V/m in Australia and 1.14 V/m in the United States of America. Corresponding downlink exposure was 0.67 V/m, 0.35 V/m, 0.29 V/m, 0.91 V/m, 0.26 V/m and 1.11 V/m in Switzerland, Ethiopia, Nepal, South Africa, Australia and the United States respectively. Mean total RF-EMF exposure for tourist areas was 0.68 V/m in Nepal, 0.60 V/m in South Africa, 1.39 V/m in Australia and 1.13 V/m in the United States of America. Corresponding downlink exposure was 0.66 V/m, 0.57 V/m, 0.39 V/m and 1.12 V/m in Nepal, South Africa, Australia and the United States respectively (Table 1). In less urban areas, such as industrial, tourist, university or rural areas, exposure tended to be lower although exceptions were observed such as the industrial areas in Cape Town and Los Angeles (Figure 3), the University area (2.51 V/m) in Canberra, the tourist area (2.01 V/m) in Sydney and the rural area (1.60 V/m) in Los Angeles (Figure 2). We also looked at average frequency-specific exposure levels in all microenvironments, including public transportation, across the six countries (Supplementary material: Table S4). For downlink exposure, mostly the 900 MHz, 1800 MHz and 2100 MHz frequency bands are used, except for the LTE Band 7 DL (2600 MHz in the United States of America).

In public transport in Switzerland and Nepal, mean total RF-EMF exposure was 0.57 V/m in trains (Switzerland), 0.38 V/m in trams (Switzerland), 0.37 V/m in buses (Switzerland), 0.86 V/m in auto rickshaw (Nepal), 0.60 V/m in taxi (Nepal), 0.50 V/m in police van (Nepal), 0.45 V/m in buses (Nepal), and 0.32 V/m in microbus (Nepal). In public transport the uplink exposure was often relevant. Corresponding uplink exposure was 0.47 V/m, 0.21 V/m, 0.22 V/m, 0.03 V/m, 0.12 V/m, 0.07 V/m, 0.24 V/m and 0.18 V/m respectively (Table 1). The exposure from WiFi 2G was generally low, with the highest measured in trains (0.05 V/m) in Switzerland.

3.2 Comparison of RF-EMF exposure levels across different cities in six countries

Figure 3 summarizes mean RF-EMF exposure levels across various cities for each type of microenvironment in the six countries. Mean total RF-EMF ranged between 0.35 and 1.90 V/m across the city centers. We found highest mean total RF-EMF in the city center of Canberra (1.90 V/m) and Sydney (1.80 V/m), followed by the city center in Addis Ababa (1.65 V/m). The main contributor to the mean total RF-EMF in these cities was broadcasting: 1.76 V/m in Canberra, 1.12 V/m in Sydney and 1.18 V/m in Addis Ababa. About 75% of the broadcasting exposure in Canberra and Sydney corresponds to the FM Radio band, while in Addis Ababa both FM Radio and TV bands contributed equally. The lowest mean total RF-EMF exposure was found in the city center of Aarau (0.35 V/m), where approximately 90% of the exposure was from downlink band. Highest downlink exposure was 1.34 V/m, which was found in the city center of Sydney, and was closely followed by 1.22 V/m in Los Angeles.

Across central residential areas, mean total RF-EMF exposure ranged between 0.53 V/m and 1.60 V/m across the central residential areas. The highest mean total RF-EMF exposure was found in the central residential area in Canberra (1.60 V/m). Most of the mean total RF-EMF was from broadcasting (1.57 V/m). Downlink exposure was found to be highest in the central residential area in Los Angeles (1.39 V/m), followed by 0.97 V/m in the central residential area in Milnerton. Mean total RF-EMF exposure in industrial areas varied between 0.10 V/m and 1.14 V/m. The highest mean total RF-EMF exposure was found in the industrial area in Los Angeles (1.14V/m), where downlink comprised 1.11 V/m. The lowest exposure was 0.10 V/m in the industrial area in Bhaktapur Nepal, where downlink comprised 0.09 V/m (Figure 3). Similarly, across rural centers, mean total RF-EMF exposure ranged between 1.60 V/m in Los Angeles and 0.12 V/m in Sydney. Corresponding downlink exposure was 1.58 V/m in Los Angeles and 0.026 V/m in Sydney. Broadcasting also significantly contributed to the mean total RF-EMF; 0.12 V/m in Sydney and 0.21 V/m in Los Angeles.

Figure 4 summarizes mean RF-EMF exposure levels across public transportation in Switzerland, Nepal and South Africa. Across various modes of public transport in Switzerland, South Africa and Australia, uplink exposure ranged between 0.03 V/m in auto rickshaw in Lalitpur and 0.56 V/m in trains in Zurich. Specifically, across train services, we found the highest uplink exposure to be 0.56 V/m in trains in Zurich and 0.44 V/m in trains in Seewen. Lowest uplink exposure was found to be 0.19 V/m in trains in Wollongong. Across tram services, we found the highest uplink exposures of 0.21 V/m in Munchenstein and Zurich. Across bus services, we found the highest uplink exposure in Kathmandu (0.34 V/m) and in Seewen (0.26 V/m), and the lowest uplink exposure in Bhaktapur (0.12 V/m). Similarly, across taxi services, the highest was 0.16 V/m in Kathmandu and the lowest uplink exposure was 0.05 V/m in Bhaktapur and Lalitpur.

3.3 Variability of RF-EMF exposure levels within same type of microenvironments

Table 2 summarizes the variability of total RF-EMF exposure levels across the same type of microenvironments of comparable outdoor microenvironments. The variability was calculated based on summary statistics for the same type of microenvironments in the same country, and then variability was summarized for different microenvironments in each country as shown in the Table 2. For total RF-EMF exposure, highest variability was found in rural residential areas in Australia (minimum 0.19 V/m, median 0.26 V/m, maximum 0.69 V/m, and coefficient of variation 1.28) and central residential areas in Australia (minimum 0.60 V/m, median 1.03 V/m, maximum 2.35 V/m, and coefficient of variation 1.10). Lowest variability across the microenvironments was observed for different city centers in Nepal (minimum 0.62 V/m, median 0.78 V/m maximum 0.79 V/m and coefficient of variation 0.25), industrial areas in Ethiopia (minimum 0.32 V/m, median 0.36 V/m, maximum 0.39 V/m, and coefficient of variation 0.25) and tourist areas in Nepal (minimum 0.59 V/m, median 0.69 V/m, maximum 0.76 V/m, and coefficient of variation 0.25).

For downlink exposure, highest variability was found in rural residential areas in Australia (minimum 0.02 V/m, median 0.09 V/m, maximum 0.41 V/m, and coefficient of variation 1.60), university areas in Ethiopia (minimum 0.14 V/m, median 0.35 V/m, maximum 0.70 V/m, and coefficient of variation 1.18), industrial areas in Australia (minimum 0.15 V/m, median 0.21 V/m, maximum 0.49 V/m, and coefficient of variation 1.16) and university areas in Australia (minimum 0.20 V/m, median 0.21 V/m, maximum 0.55 V/m, and coefficient of variation 1.16) (Supplementary material: Table S5).

3.4 Repeatability of RF-EMF exposure level

Each of the selected microenvironments was measured twice and the Spearman’s measure of association between the first and second measurement per microenvironment was calculated. Spearman’s measure of association for the first and second measurements, based on the arithmetic mean values of all outdoor microenvironments in Switzerland, was 0.97 for total RF-EMF, 0.98 for mobile phone downlink, 0.97 for uplink and 0.87 for broadcasting (Figure 5). In Ethiopia, Spearman’s measure of association was 0.71 for total RF-EMF, 0.49 for mobile phone downlink, 0.40 for uplink and 0.98 for broadcasting (Supplementary material: Figure S1). In Nepal, Spearman’s measure of association was 0.85 for total RF-EMF, 0.90 for mobile phone downlink, 0.25 for uplink and 0.90 for broadcasting (Supplementary material: Figure S2). In South Africa, Spearman’s measure of association was 0.77 for total RF-EMF, 0.72 for mobile phone downlink, 0.41 for uplink and 0.82 for broadcasting (Supplementary material: Figure S3). Similarly, in Australia, Spearman’s measure of association was 0.91 for total RF-EMF, 0.92 for mobile phone downlink, 0.89 for uplink and 0.88 for broadcasting (Supplementary material: Figure S4). We also looked into potential relationships between day and night time exposure in the United States of America. Spearman’s measure of association between day and night time measurements was 0.62 for total RF-EMF, 0.67 for mobile phone downlink, 0.69 for uplink and 0.76 for broadcasting (Figure 6).

4. Discussion

This multi-country study analyzed RF-EMF exposure levels in 94 microenvironments from six countries; Switzerland, Ethiopia, Nepal, South Africa, Australia and the United States of America. Each of the selected microenvironments was measured twice using ExpoM-RF and EME Spy 201 following a previously test protocol in Switzerland (Sagar et al., 2016). Mean total RF-EMF exposure levels across various outdoor microenvironments in the selected countries varied widely, with the highest contribution from downlink in all microenvironments except some Australian and Ethiopian microenvironments, where broadcasting contributed the most. In trains, uplink was the most relevant exposure source.

4.1 Comparison of exposure level with existing studies

Across 15 different microenvironments in Switzerland, mean total RF-EMF exposure varied between 0.22 V/m in rural residential areas and 0.69 V/m in industrial areas, which is in line with previous measurements conducted between 25th March and 11th July 2014, which were used to develop the current measurement protocol (Sagar et al., 2016). In previous international studies conducted in Europe, Swiss exposure levels were similar to measurements conducted in the Netherlands and in Belgium (Urbinello et al., 2014b). However, in the current study, Swiss exposure levels in urban areas were lower than in non-European cities. In particular, we found considerably higher exposure levels in Ethiopian, Australian and American cities. This is partly due to larger contributions of broadcasting, but downlink also tended to be higher in the non-European cities compared to Switzerland. One possible explanation for this discrepancy could be the denser building structure in Switzerland and Europe compared to the other cities. As a consequence a denser network may be installed with lower emitted power. Further, RF-EMF from base stations may not propagate as easily into street canyons as it propagates it on a more-open building environment. Similarly, across public transportation we found the highest exposure from uplink in trains (0.47 V/m) in Switzerland, then bus (0.24 V/m) in Nepal, followed by bus (0.22 V/m) and tram (0.21 V/m) in Switzerland. The differences in the uplink exposure across public transportation in the two countries could be mainly due to the fact that Switzerland is technological more advanced than Nepal where less people traveling on public transportation use smartphones. The uplink exposure levels in this study are lower than the previous measurements conducted in Switzerland (Sagar et al., 2016) and in Basel (0.97 V/m), Ghent (0.83 V/m) and Brussels (1.05 V/m) (Urbinello et al., 2014a).

Our measurements found that mobile phone base stations (downlink) generally contributed the most to the total RF-EMF in outdoor microenvironments, which is in line with previous studies conducted in Europe (Sagar et al., 2016; Urbinello, 2014c), except for some Australian and Ethiopian microenvironments where broadcasting contributed the most to the total RF-EMF exposure values. The broadcasting values from our measurement were slightly higher (1.18 V/m) in city centers in Australia than were measured (0.73 V/m) by Bhatt et al., 2016b. This difference could be due to the fact that we measured three big cities in the current study (Sydney, Canberra and Wollongong), compared to one big city by Bhatt et al., 2016b.

4.2 Strength and limitation

This multi-country non-ionizing radiation monitoring study used a common protocol (Sagar et al., 2016) in order to provide a direct comparison of RF-EMF exposures across various microenvironments in six countries; Switzerland, Ethiopia, Nepal, South Africa, Australia and the United States of America. This is the first study to globally apply the same protocol and devices (with the exception of the USA, which used different frequency bands). Nevertheless, some differences in methods were applied between countries (due to security or practicality reasons), which may hamper comparability. We conducted the measurement by driving, walking, or both. When driving, a portable exposimeter was mounted on the roof of a car and measurements taken for about 15-20 minutes. In this case, RF-EMF may be reflected from the roof and measurements may somewhat overestimate the true exposure. While walking the measurement was conducted using a backpack with the exposimeter on its top at a distance of about 20-30 cm away from the body in order to minimize body shielding. In previous studies, keeping the exposimeters close, within 10-50 mm of the body, produced underestimation of the incident field strength by about 10-50% for some frequency bands (Blas et al., 2007; Bolte & Eikelboom, 2012; Iskra et al., 2010; Knafl et al., 2008; Neubauer et al., 2007; Radon et al., 2006). To assess cross validation of the body shielding and bias, we repeated measurements in the Cape Town city center by both driving a car with the device mounted on its roof and by walking with a backpack with the device on the top. The total RF-

EMF exposure levels changed slightly 0.98 V/m whiling driving and 0.92 V/m while walking, however the difference was mainly due to an increase in uplink and broadcasting exposure levels, which in line with previous study (Bolte et al., 2016).

All the measurements were conducted by the same person, which improves reliability of the application of the procedure. This approach did not allow the various measurements to be made at the same time point, but rather were taken over a period of 3 years (from March 2015 to April 2017). Thus, if exposure on a global scale would have increased during this time period, this would bias the comparison between microenvironments. Only little research on time trends has been published so far. Whereas Urbinello et al found an increase of 57.1% in the outdoor Basel area between April 2011 and March 2012 (Urbinello et al., 2014a), no indication of such a time trend was seen in other studies (Rowley & Joyner, 2012; Sagar et al., 2017). This indicates that any potential time trend during the study period is likely to be small relative to the large variability observed between the areas.

Conducting measurements by a trained researcher brings the advantage that the own mobile phone could be turned off and thus measured uplink can be unambiguously attributed to exposure from other people’s mobile phones, which is not the case in volunteer studies (Frei et al., 2009; Viel et al., 2009).

On the other hand, this study also has some drawbacks. Our study selected only a few microenvironments for repeated measurements. Thus, our data cannot be taken as representative of the corresponding countries, which would certainly need more environments selected for measurements. It is striking that measurements were highly reproducible within the same area. This suggests that future studies do not need to invest too much time into assessing repeatability, and could profitably use the saved resource to cover more microenvironments. We used two different devices (ExpoM-RF and EME Spy 201) that were relevant to the frequency bands in the selected six countries, and this might have influenced the total RF-EMF exposure levels since the frequency bands were different for both devices. Hence, it would be useful in future research to use a device with modified frequency bands that are applicable to all of the microenvironments across all the countries assessed.

5. Conclusion

Overall, mean exposure levels in all countries are substantially below ICNIRP guideline limits for the general population (ICNIRP, 1998). This study demonstrates high RF-EMF variability between selected microenvironments, and that exposure tends to increase with increasing urban level. Most exposure comes from downlink in outdoor environments, except in Australia where broadcasting was the most important contributor. Uplink is in general not relevant in outdoor environments, however it is an important source in public transportation and exhibits large variability. WLAN was negligible in all measured microenvironments. This study demonstrates the benefit of using a common protocol to monitor RF-EMF, and, given the substantial number of measurements, provides strong conclusions regarding spatial and temporal exposure trends on a global scale.

Conflict of interest

The authors declare no conflict of interest.

Acknowledgement

This study was supported by various collaborators. The measurements in South Africa were funded by the Joint South Africa and Swiss Chair in Global Environmental Health, the measurements in Australia were funded by the National Health and Medical Research Council of Australian (Grant number 1060205), and the measurements in the United States of America were funded by the Environmental Working Group, based in Washington DC. The measurements in Nepal was partly funded by the commission for young professionals from developing countries, and Department of Education Basel-Stadt, Switzerland.

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Figure 1: Box plot showing exposure for total RF-EMF, downlink, uplink and broadcasting for eight different types of microenvironments.

Figure 2: Mean RF-EMF exposure levels across six countries for total RF-EMF, uplink, downlink, broadcasting and WiFi 2G for in six different microenvironments.

Figure 3: Mean RF-EMF exposure levels across various cities for six countries.

Figure 4: Mean RF-EMF exposure levels across public transportations.

Figure 5: Spearman correlation between the first and second measurement per microenvironment.

Figure 6: Spearman correlation between day time and night time measurement.

Table 1: Overall exposure levels across all selected microenvironments across all the six countries.

Table 2: Variability of total RF-EMF exposure levels across the same type of microenvironments of comparable outdoor microenvironments.

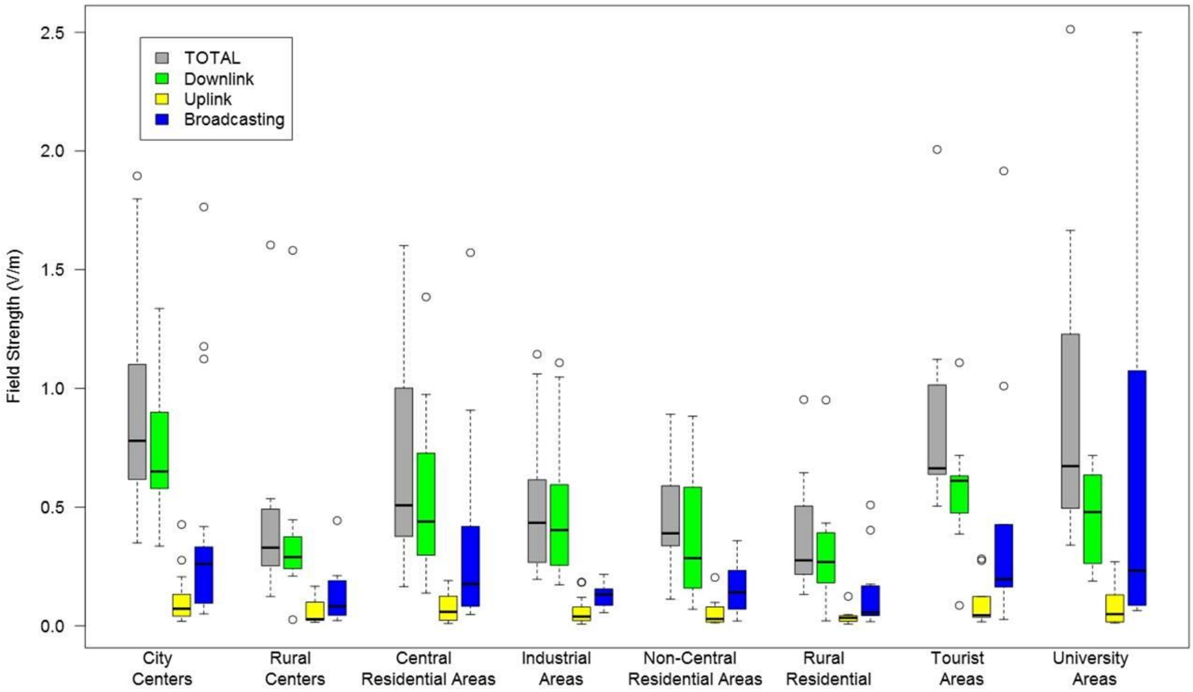

Figure 1: Box plot showing exposure for total RF-EMF, downlink, uplink and broadcasting for eight different types of microenvironments.

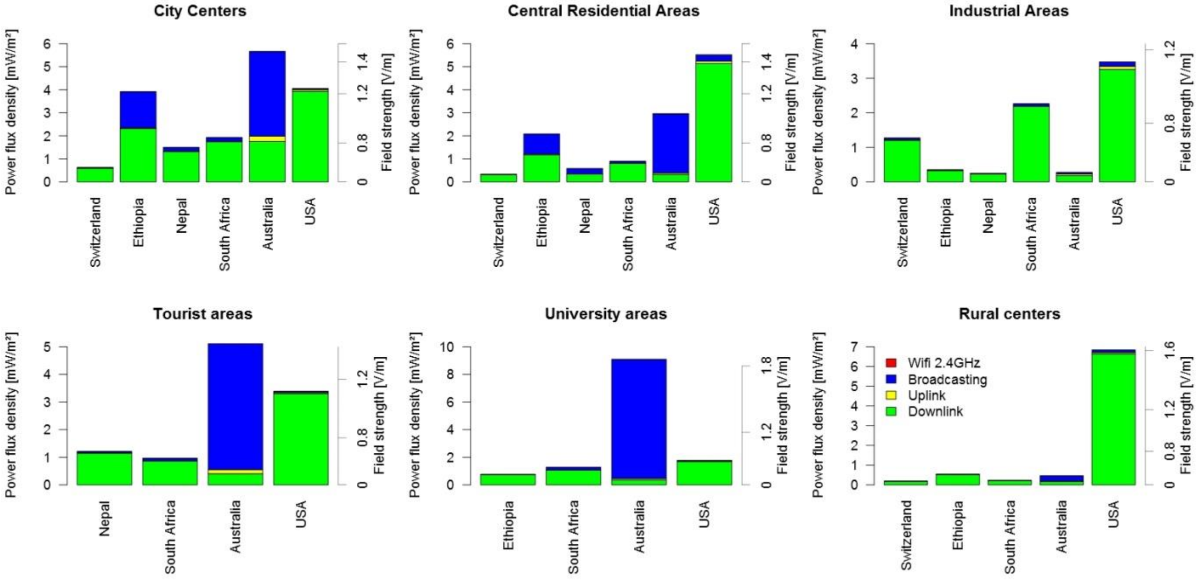

Figure 2: Mean RF-EMF exposure levels across six countries for total RF-EMF, uplink, downlink, broadcasting and WiFi 2G for in six different microenvironments.

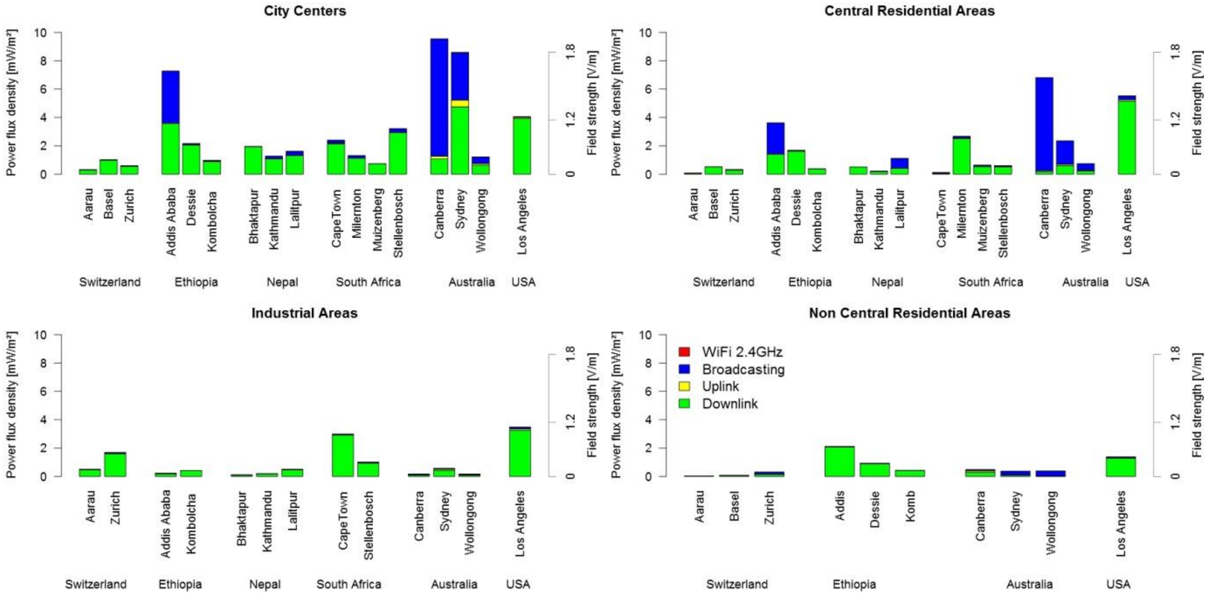

Figure 3: Mean RF-EMF exposure levels across various cities for six countries.

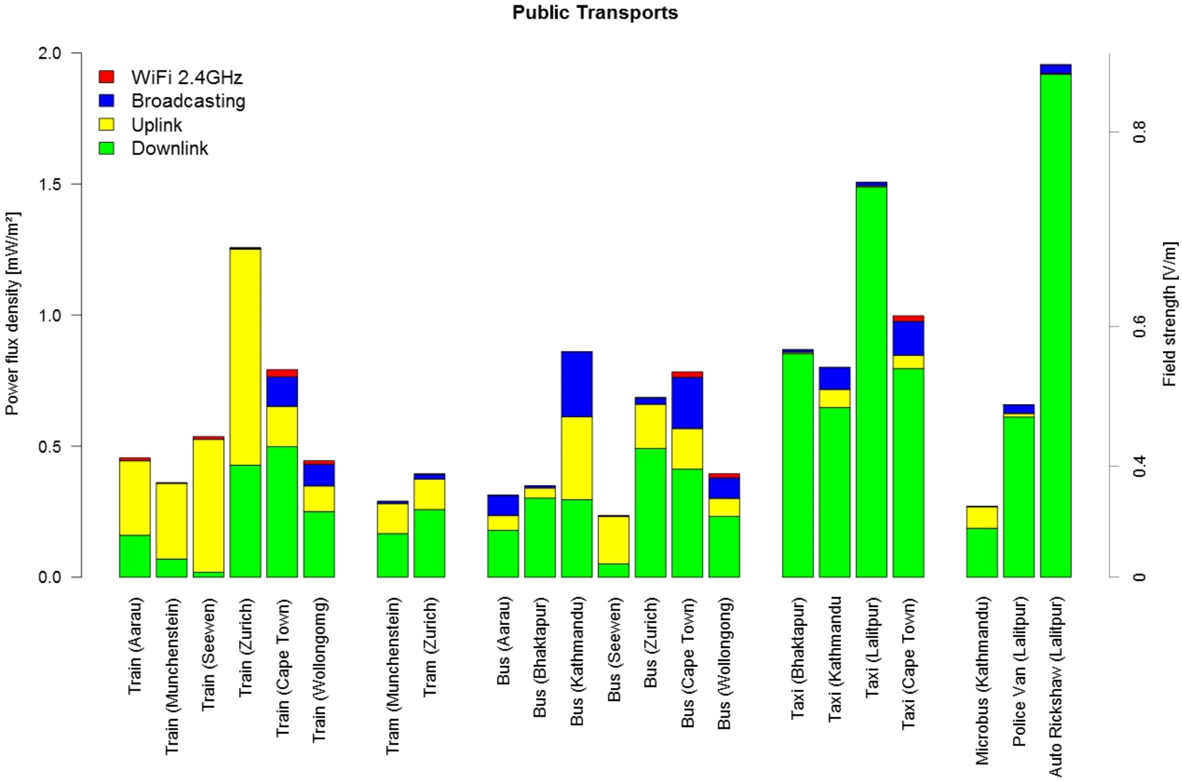

Figure 4: Mean RF-EMF exposure levels across public transportations.

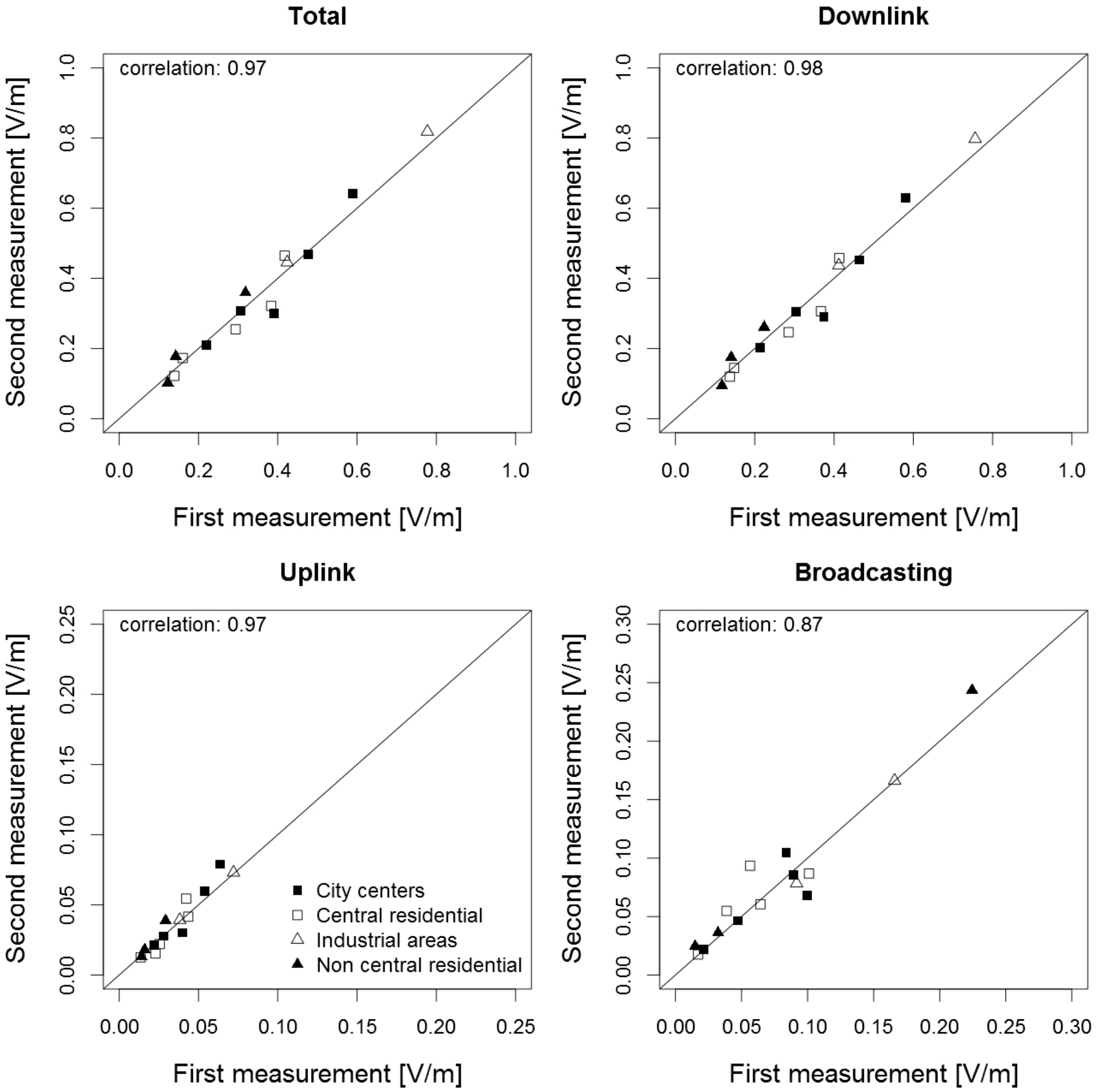

Figure 5: Spearman correlation between the first and second measurement per microenvironment.

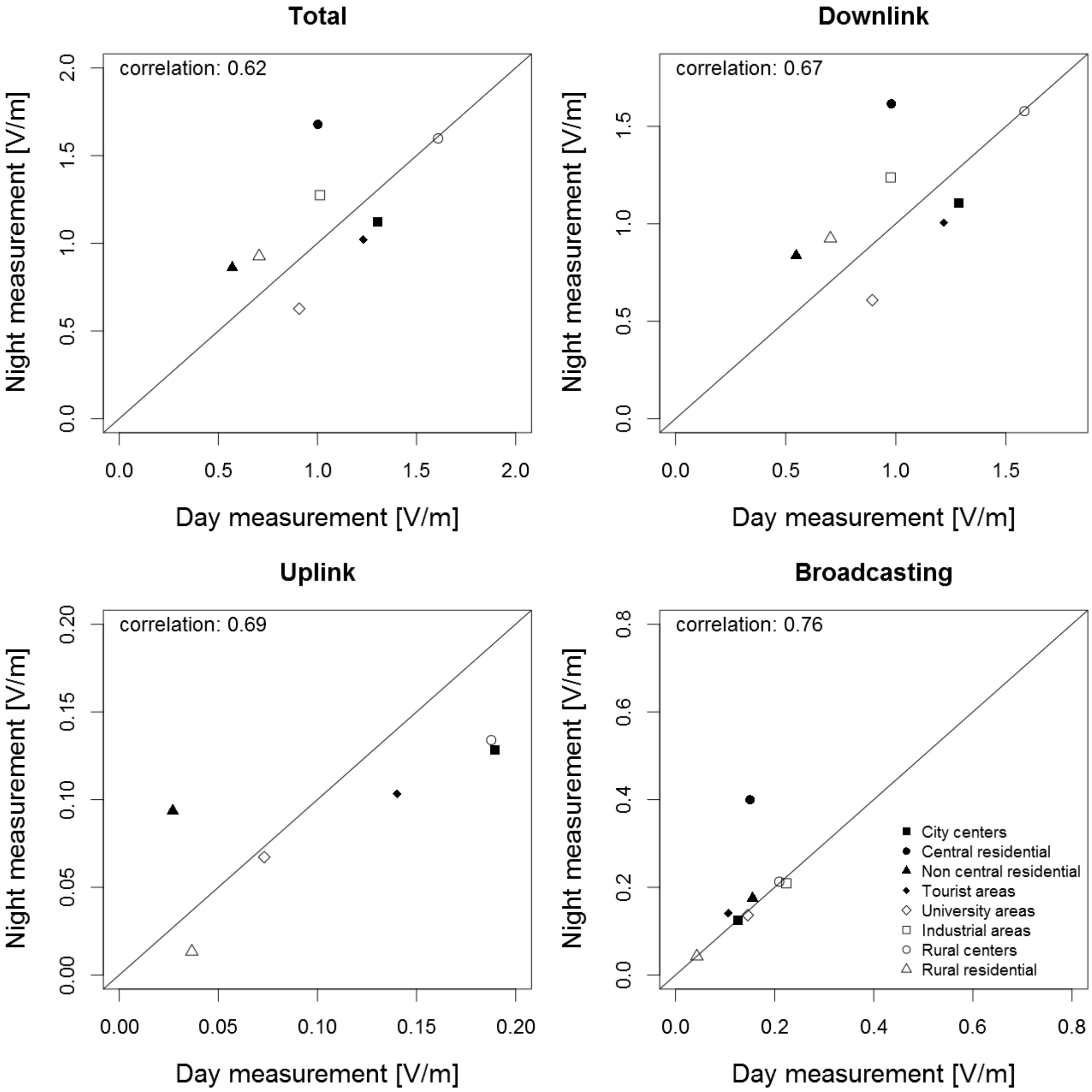

Figure 6: Spearman correlation between day time and night time measurement.

Table 1: Overall exposure levels across all selected microenvironments across all the six countries.

Table 1: Overall exposure levels across all selected microenvironments across all the six countries

Microenvironments	Country	Number of microenvironments	Total	Downlink	Uplink	Broadcasting	Wifi 2.4GHz
City centers	Switzerland	3	0.48	0.47	0.06	0.09	0.02
	Ethiopia	3	1.21	0.94	0.10	0.77	0.02
	Nepal	3	0.75	0.70	0.07	0.25	0.02
	South Africa	4	0.85	0.81	0.08	0.25	0.03
	Australia	3	1.46	0.81	0.29	1.18	0.02
	United States of America	1	1.24	1.22	0.17	0.13	0.03
Central residential areas	Switzerland	3	0.35	0.34	0.04	0.07	0.02
	Ethiopia	4	0.88	0.67	0.08	0.57	0.01
	Nepal	3	0.47	0.36	0.04	0.30	0.01
	South Africa	4	0.58	0.55	0.05	0.17	0.02
	Australia	3	1.06	0.35	0.16	0.98	0.01
	United States of America	1	1.44	1.39	0.19	0.32	0.02
Industrial areas	Switzerland	2	0.69	0.67	0.06	0.14	0.02
	Ethiopia	2	0.36	0.35	0.01	0.08	0.01
	Nepal	3	0.31	0.29	0.04	0.08	0.01
	South Africa	2	0.92	0.91	0.02	0.16	0.03
	Australia	3	0.32	0.26	0.13	0.14	0.01
	United States of America	1	1.14	1.11	0.18	0.22	0.01
Tourist areas	Nepal	3	0.68	0.66	0.06	0.14	0.02
	South Africa	2	0.60	0.57	0.02	0.19	0.02
	Australia	3	1.39	0.39	0.23	1.31	0.01
	United States of America	1	1.13	1.12	0.12	0.13	0.03
University areas	Ethiopia	3	0.53	0.53	0.03	0.08	0.01
	South Africa	2	0.69	0.64	0.02	0.27	0.03
	Australia	3	1.85	0.37	0.20	1.80	0.01
	United States of America	1	0.82	0.80	0.07	0.14	0.01
Non central residential areas	Switzerland	3	0.23	0.18	0.02	0.14	0.01
	Ethiopia	3	0.57	0.57	0.02	0.08	0.01
	Australia	3	0.39	0.20	0.14	0.30	0.01
	United States of America	1	0.72	0.70	0.07	0.16	0.01
Rural centers	Switzerland	2	0.26	0.26	0.02	0.04	0.01
	Ethiopia	1	0.45	0.45	0.01	0.04	0.01
	South Africa	1	0.29	0.28	0.02	0.04	0.01
	Australia	3	0.42	0.26	0.10	0.31	0.01
	United States of America	1	1.60	1.58	0.17	0.21	0.01
Rural residential areas	Switzerland	2	0.22	0.21	0.02	0.05	0.00
	Ethiopia	1	0.29	0.28	0.01	0.06	0.01
	South Africa	1	0.24	0.23	0.01	0.04	0.01
	Australia	3	0.32	0.20	0.07	0.24	0.01
	United States of America	1	0.82	0.82	0.03	0.04	0.02
Shopping centers	Ethiopia	2	0.61	0.58	0.15	0.09	0.01
Informal area/Khalitsha	South Africa	1	0.91	0.85	0.02	0.32	0.03
Bus	Switzerland	3 rides	0.37	0.28	0.22	0.12	0.02
Train		4 rides	0.57	0.33	0.47	0.03	0.05
Tram		3 rides	0.38	0.3	0.21	0.08	0.03
Bus	Nepal	2 rides	0.45	0.34	0.24	0.20	0.01
Microbus		1 ride	0.32	0.27	0.18	0.02	0.01
Police van		1 ride	0.50	0.48	0.07	0.11	0.01
Taxi		3 rides	0.60	0.57	0.12	0.13	0.01
Auto rickshaw		1 ride	0.86	0.85	0.03	0.11	0.02

Table 2: Variability of total RF-EMF exposure levels across the same type of microenvironments of comparable outdoor microenvironments.

Table 2: Variability of total RF-EMF exposure levels across the same type of microenvironments of comparable outdoor microenvironments

Total RF-EMF

		no. of microenvironment	mean	min	25perc	median	75perc	max	SD*	CV$^{\$}$
City centers	Switzerland	3	0.48	0.39	0.44	0.48	0.54	0.59	0.31	0.41
	Ethiopia	3	1.21	0.56	0.75	0.90	1.32	1.63	1.11	0.98
	Nepal	3	0.75	0.62	0.70	0.78	0.78	0.79	0.36	0.25
	South Africa	4	0.85	0.51	0.71	0.86	0.99	1.09	0.63	0.54
	Australia	3	1.46	0.71	1.31	1.72	2.13	2.48	1.68	0.88
Rural centers	Switzerland	2	0.26	0.22	0.24	0.27	0.29	0.31	0.18	0.45
	Australia	3	0.42	0.16	0.25	0.32	0.47	0.58	0.41	1.06
Rural residential areas	Switzerland	2	0.22	0.14	0.19	0.23	0.26	0.29	0.22	0.90
	Australia	3	0.32	0.19	0.22	0.26	0.52	0.69	0.49	1.28
Central residential areas	Switzerland	3	0.35	0.16	0.29	0.38	0.40	0.42	0.28	0.68
	Ethiopia	3	0.88	0.41	0.66	0.83	0.98	1.11	0.73	0.76
	Nepal	3	0.47	0.27	0.32	0.37	0.55	0.68	0.46	0.93
	South Africa	4	0.58	0.22	0.42	0.54	0.71	0.97	0.62	0.98
	Australia	3	1.06	0.60	0.84	1.03	1.81	2.35	1.67	1.21
Non central residential areas	Switzerland	3	0.23	0.12	0.13	0.14	0.25	0.32	0.22	1.06
	Ethiopia	3	0.57	0.37	0.47	0.55	0.74	0.88	0.57	0.81
	Australia	3	0.39	0.35	0.42	0.48	0.51	0.53	0.29	0.38
Industrial areas	Switzerland	2	0.69	0.42	0.53	0.63	0.71	0.78	0.55	0.77
	Ethiopia	2	0.36	0.32	0.34	0.36	0.37	0.39	0.18	0.25
	Nepal	3	0.31	0.15	0.22	0.27	0.37	0.45	0.31	0.95
	South Africa	2	0.92	0.63	0.76	0.87	0.96	1.05	0.70	0.66
	Australia	3	0.32	0.27	0.27	0.28	0.44	0.56	0.37	0.90
Tourist areas	Nepal	3	0.68	0.59	0.64	0.69	0.73	0.76	0.34	0.25
	South Africa	2	0.60	0.49	0.53	0.57	0.61	0.64	0.34	0.36
	Australia	3	1.39	0.80	1.12	1.37	1.90	2.31	1.56	0.93
University areas	Ethiopia	3	0.53	0.19	0.29	0.36	0.56	0.70	0.49	1.10
	South Africa	2	0.69	0.37	0.42	0.47	0.51	0.55	0.35	0.54
	Australia	3	1.85	0.87	1.41	1.80	2.45	2.97	2.03	0.97

*** Standard deviation** $^{\$}$ **CV=SD/mean**

Note: In the United States of America, we have only one microenvironment, hence we lack variability measures

Comparison of Radiofrequency Electromagnetic Field Exposure levels in different Everyday Microenvironments in an International context

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SUPPLEMENTAL MATERIAL

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Table S1: Overview of the selected microenvironments with schedule of their measurements across all the six countries

Country	Place	Measurement number	Date	Microenviroments										
				City center	Rural center	Rural residential area	Central residential area	Non-central residential area	Industrial area	Tourist area	University area	Informal setting	Shopping area	
Switzerland	Aarau	1	11.03.2015	Bahnhof strasse, Laurenzentorgasse-Pelzgasse, Rathausgasse-Kirchgasse			Halden-Zollrain, Kirchgasse and Kirchgasse	Keba, Hombergstrasse-Goldernstrasse	Neumattstrasse					All measurements by walking
	Aarau	2	14.03.2015											
	Basel	1	31.03.2015	Barfusserplatz, Markplatz and Claraplatz			Gundeldingen and Byfangweg	Im Langen Loh						
	Basel	2	02.04.2015											
	Muenchenstein	1	18.03.2015		Münchenstein Dorf, Hauptstrasse	Gruthweg, Zergweg, Rebgasse and Pfarrgasse								
	Muenchenstein	2	20.03.2015											
	Seewen	1	18.03.2015		Seewen city center	Away from city center								
	Seewen	2	20.03.2015											
	Zurich	1	10.03.2015	Münstergasse-Römergasse,Bahnhofstrasse-Schweizergasse			Stauffacher station, Engelstrasse-Wengisstrasse	Toblerplatz, Mommsenstrasse-Rislingsstrasse	Escher-Wyss-Platz, Pfingstweidstrasse					
	Zurich	2	13.03.2015											
Ethiopia	Addis Ababa	1	27.09.2015	Paissa,Merkato,Autobus Tera and American Gibi			Afincho Ber, Semen Hotel	Bollie	Ye endustry mender		Sidistkillo University		Dembelcentre, Kurtu Commercial Center	All measurements by driving
	Addis Ababa	2	07.10.2015											
	Dessie	1	30.09.2015	Piassa, Arada, Sherftera			Dawudo, Hospital and Menafesha				Wollo University		Arada	All measurement by walking
	Dessie	2	03.10.2015											
	Haik	1	01.10.2015		Haik city center	Away from city center								
	Haik	2	04.10.2015											
	Kombolcha	1	29.09.2015	Piassa, Menaheria			Berberiewonz	Shewaber	Kospi, Cherkacherk		Wollo universit		konmbolcha shoping	

	Kombolcha	2	05.10.2015								y kombolcha campus		center	
Nepal	Bhaktapur	1	15.11.2015	Kaushaltar			Balkot		Bhaktapur Industrial area	Bhaktapur Durbar Square				All measurements by walking
	Bhaktapur	2	22.11.2015											
	Kathmandu	1	08.11.2015	Kingsway around Royal Palace			Ramkot		Balaju Industrial area	Thamel				
	Kathmandu	2	11.11.2015											
	Lalitpur	1	14.11.2015	Jwalakhel area			Area behind satdobato		Patan Industrial area	Patan Square				
	Lalitpur	2	21.11.2015											
South Africa	Cape Town	1	06.05.2016	Adderley St., Long St., Strand St			Rondenbosch		Epping industrial areas	Waterfront	UCT upper campus			All measurements by driving
	Cape Town	2	12.05.2016											
	Grabouw	1	03.05.2016		Main market	Outside main market								
	Grabouw	2	04.05.2016											
	Khayelitsha	1	16.05.2016									all areas		
	Khayelitsha	2	20.05.2016											
	Milnerton	1	16.05.2016	Canal walk/Century mall area			Marconi beam area							
	Milnerton	2	20.05.2016											
	Muizenberg	1	17.05.2016	Train station, beach road			Valbaai							
	Muizenberg	2	24.05.2016											
	Stellenbosch	1	03.05.2016	Eikestad Mall and Town hall			Dalsig area		Wine route	Village muesum, Botanical garden	Rhennis school area			
	Stellenbosch	2	04.05.2016											
Australia	Canberra	1	06.10.2016	Civic Square	Queenbeyan city center	Queenbeyan into residential areas	Braddon	Greenway	Hume Industrial Estate	Parliament House	Australian National University			All measurement by drivings
	Canberra	2	20.10.2016											
	Sydney	1	05.10.2016	Martin Place	Bundeena city center	Bundeena awy	Surry Hills	Sutherlands	Taren point	The Rocks market	Universit			

	Sydney	2	19.10.2016			into residential areas					y of Sydney			
	Wollongong	1	30.09.2016	Wollongong central	Albion Park city center	Albion Park away into residential areas	Smith st, Mar st and Cliff rd	Woonona	Port Kembla steel areas	Breakwater Lighthouse and Stuart park	University of Wollongong			
	Wollongong	2	14.10.2016											
United States of America**	Los Angeles	1	31.03.2017	Wilshire Blvd, La Brea tar Pits and Museum, Mac author park										All measurements by driving
	Los Angeles	2	05.04.2017											
	Los Angeles	1	12.04.2017		Foot hill blvd									
	Los Angeles	2	14.04.2017											
	Los Angeles	1	12.04.2017			Hill haven ave								
	Los Angeles	2	14.04.2017											
	Los Angeles	1	05.04.2017				W Florance Ave, S Vermont Ave, W centruy Bld, S Van Ness Ave							
	Los Angeles	2	12.04.2017											
	Los Angeles	1	05.04.2017					Beverley Hills , Sunset Blvd, Harvrad westlake middle upper school						
	Los Angeles	2	06.04.2017											
	Los Angeles	1	05.04.2017						S Alameda , Slauson Ave, S Downey, E Washington Blvd, Leonis Blvd					
	Los Angeles	2	12.04.2017											
	Los Angeles	1	04.04.2017							Venice beach, hotel erwin				
	Los Angeles	2	05.04.2017											
	Los Angeles	1	05.04.2017								UCLA			
	Los Angeles	2	06.04.2017											

** All first measurements taken during day light time between 9am and 5pm and all second measurement taken during evening between 7pm and 9pm

Table S2: Overview of frequency bands and measuring range of Expom, ExpoM-RF and EME Spy 201

Expom Frequencies	**Frequency bands**	**Frequency range**	**Dynamic range**	
	DVB-T	470 - 790 MHz	0.01 V/m	5 V/m
	LTE800.DL	791 - 821 MHz	0.005 V/m	5 V/m
	LTE800.UL	832 - 862 MHz	0.005 V/m	5 V/m
	GSM900.TX	880 - 915 MHz	0.015 V/m	5 V/m
	GSM900.RX	925 - 960 MHz	0.015 V/m	5 V/m
	GSM1800.TX	1710 - 1785 MHz	0.01 V/m	5 V/m
	GSM1800.RX	1805 - 1880 MHz	0.005 V/m	5 V/m
	DECT	1880 - 1900 MHz	0.005 V/m	5 V/m
	UMTS.TX	1920 - 1980 MHz	0.003 V/m	5 V/m
	UMTS.RX	2110 - 2170 MHz	0.01 V/m	5 V/m
	ISM.2.4	2400 - 2485 MHz	0.005 V/m	5 V/m
	LTE.2600	2500 - 2690 MHz	0.025 V/m	5 V/m
	WiMax 3.5 GHz	3400 - 3600 MHz	0.05 V/m	5 V/m

ExpoM-RF Frequencies	**Frequency bands**	**Frequency range**	**Dynamic range**	
	FM Radio	87.5 – 108 MHz	0.02 V/m	5 V/m
	DVB-T	470 – 790 MHz	0.005 V/m	5 V/m
	Mobile 800 MHz downlink	791 – 821 MHz	0.005 V/m	5 V/m
	Mobile 800 MHz uplink	832 – 862 MHz	0.005 V/m	5 V/m
	Mobile 900 MHz uplink	880 – 915 MHz	0.005 V/m	5 V/m
	Mobile 900 MHz downlink	925 – 960 MHz	0.005 V/m	5 V/m
	Mobile 1800 MHz uplink	1710 – 1785 MHz	0.005 V/m	5 V/m
	Mobile 1800 MHz downlink	1805 – 1880 MHz	0.005 V/m	5 V/m
	DECT	1880 – 1900 MHz	0.005 V/m	5 V/m
	Mobile 2.1 GHz uplink	1920 – 1980 MHz	0.003 V/m	5 V/m
	Mobile 2.1 GHz downlink	2110 – 2170 MHz	0.003 V/m	5 V/m
	ISM 2.4 GHz	2400 – 2485 MHz	0.005 V/m	5 V/m
	Mobile 2.6 GHz uplink	2500 – 2570 MHz	0.003 V/m	5 V/m
	Mobile 2.6 GHz downlink	2620 – 2690 MHz	0.003 V/m	5 V/m
	Mobile 3.5 GHz	3400 – 3600 MHz	0.003 V/m	3 V/m
	ISM 5.8 GHz / U-NII 1-2e	5150 – 5875 MHz	0.05 V/m	5 V/m

EME Spy 201 Frequencies	**Frequency bands**	**Frequency range**	**Dynamic range**	
	FM	88 - 108	0.015 V/m	6 V/m
	TV-VHF	174 - 216	0.015 V/m	6 V/m
	TV-UHF	470 - 644	0.005 V/m	6 V/m

	LTE Band 12 UL	698 - 716	0.005 V/m	6 V/m
	LTE Band 12 DL	728 - 746	0.005 V/m	6 V/m
	LTE Band 13 DL	746 - 756	0.005 V/m	6 V/m
	LTE Band 13 UL	777 - 787	0.005 V/m	6 V/m
	LTE Band 5 UL	824 - 849	0.005 V/m	6 V/m
	LTE Band 5 DL	869 - 894	0.005 V/m	6 V/m
	ISM/Smart meters	902 - 928	0.005 V/m	6 V/m
	LTE Band 4 UL	1710 - 1755	0.005 V/m	6 V/m
	LTE Band 2 UL	1850 - 1910	0.005 V/m	6 V/m
	DECT 6.0	1920 - 1930	0.005 V/m	6 V/m
	LTE Band 2 DL	1930 - 1990	0.005 V/m	6 V/m
	LTE Band 4 DL	2110 - 2155	0.005 V/m	6 V/m
	LTE Band 40	2300 - 2400	0.005 V/m	6 V/m
	WiFi 2G	2400 - 2483	0.005 V/m	6 V/m
	LTE Band 7 UL	2500 - 2570	0.005 V/m	6 V/m
	LTE Band 7 DL	2620 - 2690	0.005 V/m	6 V/m
	WiFi 5G	5150 - 5850	0.015 V/m	6 V/m

Table S3: Five main groups of bands: downlink, uplink, broadcasting, other (WiFi 2G) and total RF-EMF for individual frequency bands used in the respective countries

	Band	Frequency bands	Frequency range	Detection limit	
Switzerland (Expom Device)	Downlink	LTE800.DL	791 - 821 MHz	0.005 V/m	5 V/m
		GSM900.RX	925 - 960 MHz	0.015 V/m	5 V/m
		GSM1800.RX	1805 - 1880 MHz	0.005 V/m	5 V/m
		UMTS.RX	2110 - 2170 MHz	0.01 V/m	5 V/m
		LTE.2600	2500 - 2690 MHz	0.025 V/m	5 V/m
	Uplink	LTE800.UL	832 - 862 MHz	0.005 V/m	5 V/m
		GSM900.TX	880 - 915 MHz	0.015 V/m	5 V/m
		GSM1800.TX + GSM1800.TX.1	1710 - 1785 MHz	0.01 V/m	5 V/m
		UMTS.TX + UMTS.TX.1	1920 - 1980 MHz	0.003 V/m	5 V/m
	Broadcasting	DVB.T + DVB.T.1	470 - 790 MHz	0.01 V/m	5 V/m
	Wifi	ISM.2.4	2400 - 2485 MHz	0.005 V/m	5 V/m
	Total = Downlink + Uplink + Broadcasting + Wifi				

	Band	Frequency bands	Frequency range	Dynamic range	
Ethiopia (ExpoM RF Device)	Downlink	Mobile.900.MHz.Downlink	925 - 960 MHz	0.005 V/m	5 V/m
		Mobile.1.8.GHz.Downlink	1805 - 1880 MHz	0.005 V/m	5 V/m
		Mobile.2.1.GHz.Downlink	2110 - 2170 MHz	0.003V/m	5 V/m
	Uplink	Mobile.800.MHz.Uplink	832 - 862 MHz	0.005 V/m	5 V/m
		Mobile.900.MHz.Uplink	880 - 915 MHz	0.005 V/m	5 V/m
	Broadcasting	FM.Radio	87.5 - 108 MHz	0.02 V/m	5 V/m
		TV	470 - 790 MHz	0.005 V/m	5 V/m
	Wifi	ISM.2.4.GHz	2400 - 2485 MHz	0.005 V/m	5 V/m
	Total = Downlink + Uplink + Broadcasting + Wifi				

	Band	Frequency bands	Frequency range	Dynamic range	
Nepal (ExpoM RF Device)	Downlink	Mobile.900.MHz.Downlink	925 - 960 MHz	0.005 V/m	5 V/m
		Mobile.1.8.GHz.Downlink	1805 - 1880 MHz	0.005 V/m	5 V/m
		Mobile.2.1.GHz.Downlink	2110 - 2170 MHz	0.003V/m	5 V/m
	Uplink	Mobile.800.MHz.Uplink	832 - 862 MHz	0.005 V/m	5 V/m

		Mobile.1800.MHz.Uplink	1710 - 1785 MHz	0.005 V/m	5 V/m
		Mobile.2.1.GHz.Uplink	1920 - 1980 MHz	0.003 V/m	5 V/m
	Broadcasting	FM.Radio	87.5 - 108 MHz	0.02 V/m	5 V/m
		TV	470 - 790 MHz	0.005 V/m	5 V/m
	Wifi	ISM.2.4.GHz	2400 - 2485 MHz	0.005 V/m	5 V/m
	Total = Downlink + Uplink + Broadcasting + Wifi				

	Band	Frequency bands	Frequency range	Dynamic range	
South Africa (ExpoM RF Device)	Downlink	Mobile.900.MHz.Downlink	925 - 960 MHz	0.005 V/m	5 V/m
		Mobile.1.8.GHz.Downlink	1805 - 1880 MHz	0.005 V/m	5 V/m
		Mobile.2.1.GHz.Downlink	2110 - 2170 MHz	0.003V/m	5 V/m
	Uplink	Mobile.900.MHz.Uplink	832 - 862 MHz	0.005 V/m	5 V/m
		Mobile.1800.MHz.Uplink	1710 - 1785 MHz	0.005 V/m	5 V/m
		Mobile.2.1.GHz.Uplink	1920 - 1980 MHz	0.003 V/m	5 V/m
	Broadcasting	FM.Radio	87.5 - 108 MHz	0.02 V/m	5 V/m
		TV	470 - 790 MHz	0.005 V/m	5 V/m
	Wifi	ISM.2.4.GHz	2400 - 2485 MHz	0.005 V/m	5 V/m
	Total = Downlink + Uplink + Broadcasting + Wifi				

	Band	Frequency bands	Frequency range	Dynamic range	
Australia (ExpoM RF Device)	Downlink	Mobile.900.MHz.Downlink	925 - 960 MHz	0.005 V/m	5 V/m
		Mobile.1.8.GHz.Downlink	1805 - 1880 MHz	0.005 V/m	5 V/m
		Mobile.2.1.GHz.Downlink	2110 - 2170 MHz	0.003V/m	5 V/m
		Mobile.2.6.GHz.Downlink	2620 - 2690 MHz	0.003V/m	5 V/m
	Uplink	Mobile.800.MHz.Uplink	832 - 862 MHz	0.005 V/m	5 V/m
		Mobile.900.MHz.Uplink	880 - 915 MHz	0.005 V/m	5 V/m
	Broadcasting	FM.Radio	87.5 - 108 MHz	0.02 V/m	5 V/m
		TV	470 - 790 MHz	0.005 V/m	5 V/m
	Wifi	ISM.2.4.GHz	2400 - 2485 MHz	0.005 V/m	5 V/m
	Total = Downlink + Uplink + Broadcasting + Wifi				

	Band	Frequency bands	Frequency range	Dynamic range	

USA (EME Spy 201 Device)	Downlink	LTE Band 12 DL	728 - 746	0.005 V/m	6 V/m
		LTE Band 13 DL	746 - 756	0.005 V/m	6 V/m
		LTE Band 5 DL	869 - 894	0.005 V/m	6 V/m
		LTE Band 2 DL	1930 - 1990	0.005 V/m	6 V/m
		LTE Band 4 DL	2110 - 2155	0.005 V/m	6 V/m
		LTE Band 7 UL	2500 - 2570	0.005 V/m	6 V/m
	Uplink	LTE Band 12 UL	698 - 716	0.005 V/m	6 V/m
		LTE Band 13 UL	777 - 787	0.005 V/m	6 V/m
		LTE Band 5 UL	824 - 849	0.005 V/m	6 V/m
		LTE Band 4 UL	1710 - 1755	0.005 V/m	6 V/m
		LTE Band 2 UL	1850 - 1910	0.005 V/m	6 V/m
		LTE Band 7 UL	2500 - 2570	0.005 V/m	6 V/m
	Broadcasting	FM	88 - 108	0.015 V/m	6 V/m
		TV-VHF	174 - 216	0.015 V/m	6 V/m
		TV-UHF	470 - 644	0.005 V/m	6 V/m
	Wifi	WiFi 2G	2400 - 2483	0.005 V/m	6 V/m
	Total = Downlink + Uplink + Broadcasting + Wifi				

Table S4: Average exposure levels per individual frequency bands per type of microenvironments including public transports (all values are in V/m)

	Frequency bands	City centers	Central residential areas	Non central residential areas	Industrial areas	Rural centers	Rural residential areas	Train	Tram	Bus
Switzerland	LTE800.UL	0.01	0.01	0.01	0.02	0.01	0.00	0.06	0.02	0.03
	LTE800.DL	0.04	0.05	0.01	0.09	0.07	0.08	0.01	0.02	0.10
	DVB.T	0.06	0.04	0.10	0.10	0.02	0.03	0.02	0.05	0.09
	GSM900.RX	0.37	0.12	0.06	0.47	0.16	0.17	0.13	0.17	0.16
	GSM1800.TX	0.03	0.03	0.01	0.03	0.01	0.01	0.19	0.11	0.11
	DVB.T.1	0.06	0.05	0.10	0.10	0.03	0.03	0.02	0.06	0.09
	UMTS.TX	0.01	0.01	0.01	0.00	0.00	0.00	0.20	0.08	0.04
	UMTS.RX	0.21	0.15	0.13	0.39	0.15	0.03	0.24	0.17	0.16
	GSM900.TX	0.03	0.01	0.01	0.02	0.01	0.01	0.27	0.10	0.14
	LTE.2600	0.02	0.02	0.02	0.02	0.01	0.01	0.04	0.03	0.02
	ISM.2.4	0.02	0.02	0.01	0.02	0.01	0.00	0.05	0.03	0.02
	GSM1800.RX	0.20	0.27	0.10	0.26	0.11	0.10	0.18	0.18	0.12
	GSM1800.TX.1	0.04	0.02	0.02	0.04	0.02	0.01	0.18	0.10	0.10
	UMTS.TX.1	0.01	0.01	0.00	0.00	0.00	0.00	0.18	0.07	0.04
	Total RF-EMF	**0.48**	**0.35**	**0.23**	**0.69**	**0.26**	**0.22**	**0.57**	**0.38**	**0.37**

	Frequency bands	City centers	Central residential areas	Non central residential areas	Industrial areas	University areas	Shopping areas	Rural centers	Rural residential areas
Ethiopia	FM.Radio	0.54	0.36	0.09	0.08	0.07	0.08	0.04	0.05
	TV	0.54	0.45	0.03	0.01	0.02	0.04	0.00	0.00
	Mobile.800.MHz.Uplink	0.03	0.04	0.00	0.00	0.01	0.04	0.01	0.00
	Mobile.900.MHz.Uplink	0.09	0.07	0.02	0.01	0.03	0.15	0.01	0.01
	Mobile.900.MHz.Downlink	0.56	0.45	0.36	0.31	0.39	0.37	0.25	0.18

	Mobile.1.8.GHz.Downlink	0.57	0.35	0.36	0.12	0.29	0.44	0.37	0.22
	Mobile.2.1.GHz.Downlink	0.49	0.35	0.36	0.12	0.19	0.11	0.04	0.01
	ISM.2.4.GHz	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01
	Total RF-EMF	**1.21**	**0.88**	**0.57**	**0.36**	**0.53**	**0.61**	**0.45**	**0.29**

	Frequency bands	City centers	Central residential areas	Tourist areas	Industrial areas	Bus	Microbus	Tempoo	Police Van	Taxi
Nepal	FM.Radio	0.18	0.30	0.13	0.07	0.15	0.01	0.09	0.10	0.07
	TV	0.17	0.03	0.05	0.04	0.13	0.02	0.07	0.05	0.11
	Mobile.800.MHz.Uplink	0.01	0.01	0.01	0.02	0.01	0.00	0.02	0.01	0.02
	Mobile.900.MHz.Downlink	0.55	0.27	0.49	0.16	0.25	0.17	0.69	0.36	0.42
	Mobile.1.8.GHz.Uplink	0.07	0.04	0.05	0.03	0.23	0.18	0.02	0.03	0.12
	Mobile.1.8.GHz.Downlink	0.36	0.20	0.38	0.21	0.18	0.16	0.46	0.26	0.33
	Mobile.2.1.GHz.Uplink	0.01	0.02	0.01	0.00	0.01	0.02	0.00	0.06	0.02
	Mobile.2.1.GHz.Downlink	0.26	0.12	0.24	0.11	0.13	0.12	0.21	0.18	0.21
	ISM.2.4.GHz	0.02	0.01	0.02	0.01	0.01	0.01	0.02	0.01	0.01
	Total RF-EMF	**0.75**	**0.47**	**0.68**	**0.31**	**0.45**	**0.32**	**0.86**	**0.50**	**0.60**

	Frequency bands	City centers	Central residential areas	Tourist areas	Industrial areas	Rural centers	Rural residential areas	University areas	Informal area (Khalitshya)
South Africa	FM.Radio	0.06	0.08	0.03	0.07	0.02	0.02	0.08	0.31
	TV	0.24	0.15	0.19	0.14	0.04	0.04	0.26	0.09
	Mobile.900.MHz.Uplink	0.08	0.01	0.01	0.01	0.01	0.01	0.01	0.01
	Mobile.900.MHz.Downlink	0.56	0.39	0.39	0.64	0.26	0.21	0.40	0.66
	Mobile.1.8.GHz.Uplink	0.02	0.03	0.01	0.01	0.00	0.00	0.01	0.01
	Mobile.1.8.GHz.Downlink	0.48	0.34	0.35	0.56	0.02	0.03	0.34	0.45
	Mobile.2.1.GHz.Uplink	0.02	0.04	0.01	0.01	0.02	0.00	0.02	0.01
	Mobile.2.1.GHz.Downlink	0.33	0.20	0.23	0.32	0.10	0.09	0.36	0.29

	ISM.2.4.GHz	0.03	0.02	0.02	0.03	0.01	0.01	0.03	0.03
	Total RF-EMF	**0.85**	**0.58**	**0.60**	**0.92**	**0.29**	**0.24**	**0.69**	**0.91**

	Frequency bands	City centers	Central residential areas	Non central residential areas	Industrial areas	Rural centers	Rural residential areas	Tourist areas	University areas
Australia	FM.Radio	1.14	0.97	0.29	0.10	0.27	0.17	1.30	1.79
	TV	0.29	0.17	0.09	0.09	0.17	0.17	0.16	0.19
	Mobile.800.MHz.Uplink	0.06	0.03	0.04	0.04	0.03	0.04	0.04	0.03
	Mobile.900.MHz.Uplink	0.29	0.15	0.13	0.13	0.09	0.06	0.23	0.19
	Mobile.900.MHz.Downlink	0.31	0.14	0.10	0.12	0.15	0.11	0.15	0.16
	Mobile.1.8.GHz.Downlink	0.52	0.21	0.14	0.19	0.14	0.11	0.24	0.24
	Mobile.2.1.GHz.Downlink	0.51	0.23	0.11	0.14	0.16	0.11	0.26	0.22
	ISM.2.4.GHz	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01
	Total RF-EMF	**1.46**	**1.06**	**0.39**	**0.32**	**0.42**	**0.32**	**1.39**	**1.85**

	Frequency bands	City centers	Central residential areas	Non central residential areas	Industrial areas	Rural centers	Rural residential areas	Tourist areas	University areas
United States of America	FM	0.10	0.08	0.15	0.09	0.16	0.02	0.06	0.10
	TV.UHF	0.07	0.29	0.03	0.13	0.10	0.03	0.09	0.03
	TV.VHF	0.04	0.10	0.07	0.15	0.08	0.02	0.06	0.10
	LTE.B12..UL.	0.08	0.02	0.01	0.04	0.01	0.01	0.07	0.01
	LTE.B12..DL.	0.44	0.40	0.29	0.45	0.87	0.32	0.25	0.29
	LTE.B13..DL.	0.35	0.31	0.22	0.41	0.58	0.22	0.20	0.24
	LTE.B13..UL.	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00
	LTE.B5..UL.	0.01	0.02	0.01	0.01	0.04	0.01	0.02	0.04
	LTE.B5..DL.	0.41	0.32	0.37	0.15	0.52	0.17	0.29	0.31
	LTE.B4..UL.	0.01	0.01	0.01	0.01	0.01	0.00	0.01	0.01
	LTE.B2..UL.	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01

	LTE.B2..DL.	0.67	0.82	0.37	0.60	0.64	0.45	0.64	0.38
	LTE.B4..DL.	0.73	0.95	0.29	0.69	0.85	0.55	0.80	0.50
	WIFI.2G	0.03	0.02	0.01	0.01	0.01	0.02	0.03	0.01
	LTE.B7..UL.	0.15	0.19	0.07	0.18	0.16	0.02	0.10	0.06
	LTE.B7..DL.	0.06	0.01	0.01	0.01	0.01	0.00	0.02	0.01
	Total RF-EMF	**1.24**	**1.44**	**0.72**	**1.14**	**1.60**	**0.82**	**1.13**	**0.82**

Table S5: Distribution and variability of country specific mean RF-EMF exposure levels per type of microenvironment (all values are in V/m, except for the coefficient of variation CV)

Downlink										
		no. of microenvironment	**mean**	**min**	**25perc**	**median**	**75perc**	**max**	**SD***	**CV$^{\$}$**
City centers	Switzerland	3	0.47	0.37	0.42	0.46	0.53	0.58	0.32	0.43
	Ethiopia	3	0.94	0.53	0.73	0.88	0.92	0.96	0.58	0.51
	Nepal	3	0.69	0.60	0.64	0.68	0.74	0.79	0.36	0.27
	South Africa	4	0.81	0.50	0.66	0.82	0.96	1.05	0.61	0.55
	Australia	3	0.81	0.47	0.60	0.71	0.98	1.20	0.80	0.88
Rural centers	Switzerland	2	0.26	0.21	0.24	0.26	0.28	0.30	0.18	0.48
	Australia	3	0.21	0.03	0.16	0.22	0.26	0.29	0.20	0.94
Rural residential areas	Switzerland	2	0.22	0.14	0.19	0.22	0.26	0.29	0.21	0.88
	Australia	3	0.25	0.02	0.07	0.09	0.30	0.41	0.31	1.60
Central residential areas	Switzerland	3	0.34	0.15	0.28	0.37	0.39	0.41	0.28	0.71
	Ethiopia	3	0.67	0.41	0.56	0.68	0.75	0.82	0.50	0.59
	Nepal	3	0.36	0.27	0.32	0.37	0.38	0.38	0.20	0.35
	South Africa	4	0.55	0.17	0.36	0.50	0.69	0.94	0.61	1.07
	Australia	3	0.35	0.27	0.31	0.35	0.42	0.49	0.29	0.60
Non central residential areas	Switzerland	3	0.18	0.12	0.13	0.14	0.19	0.22	0.14	0.70
	Ethiopia	3	0.57	0.36	0.46	0.54	0.73	0.87	0.57	0.82
	Australia	3	0.20	0.07	0.13	0.17	0.21	0.24	0.16	0.87
dustrial area	Switzerland	2	0.67	0.41	0.52	0.61	0.69	0.76	0.53	0.77

	Ethiopia	2	0.34	0.30	0.32	0.34	0.36	0.38	0.20	0.36
	Nepal	3	0.29	0.14	0.21	0.26	0.35	0.43	0.29	0.94
	South Africa	2	0.91	0.61	0.74	0.85	0.95	1.04	0.70	0.68
	Australia	3	0.26	0.15	0.19	0.21	0.38	0.49	0.35	1.16
Tourist areas	Nepal	3	0.66	0.56	0.61	0.66	0.72	0.76	0.37	0.30
	South Africa	2	0.57	0.47	0.51	0.54	0.58	0.61	0.33	0.37
	Australia	3	0.39	0.05	0.27	0.37	0.50	0.60	0.42	1.08
University areas	Ethiopia	3	0.53	0.14	0.27	0.35	0.55	0.70	0.50	1.18
	South Africa	2	0.64	0.23	0.34	0.41	0.48	0.54	0.41	0.96
	Australia	3	0.37	0.20	0.21	0.21	0.42	0.55	0.39	1.16

*** Standard deviation** $^{\$}$ **CV=SD/mean**

Note: In the United States of America, we have only one microenvironment, hence we lack variability measures

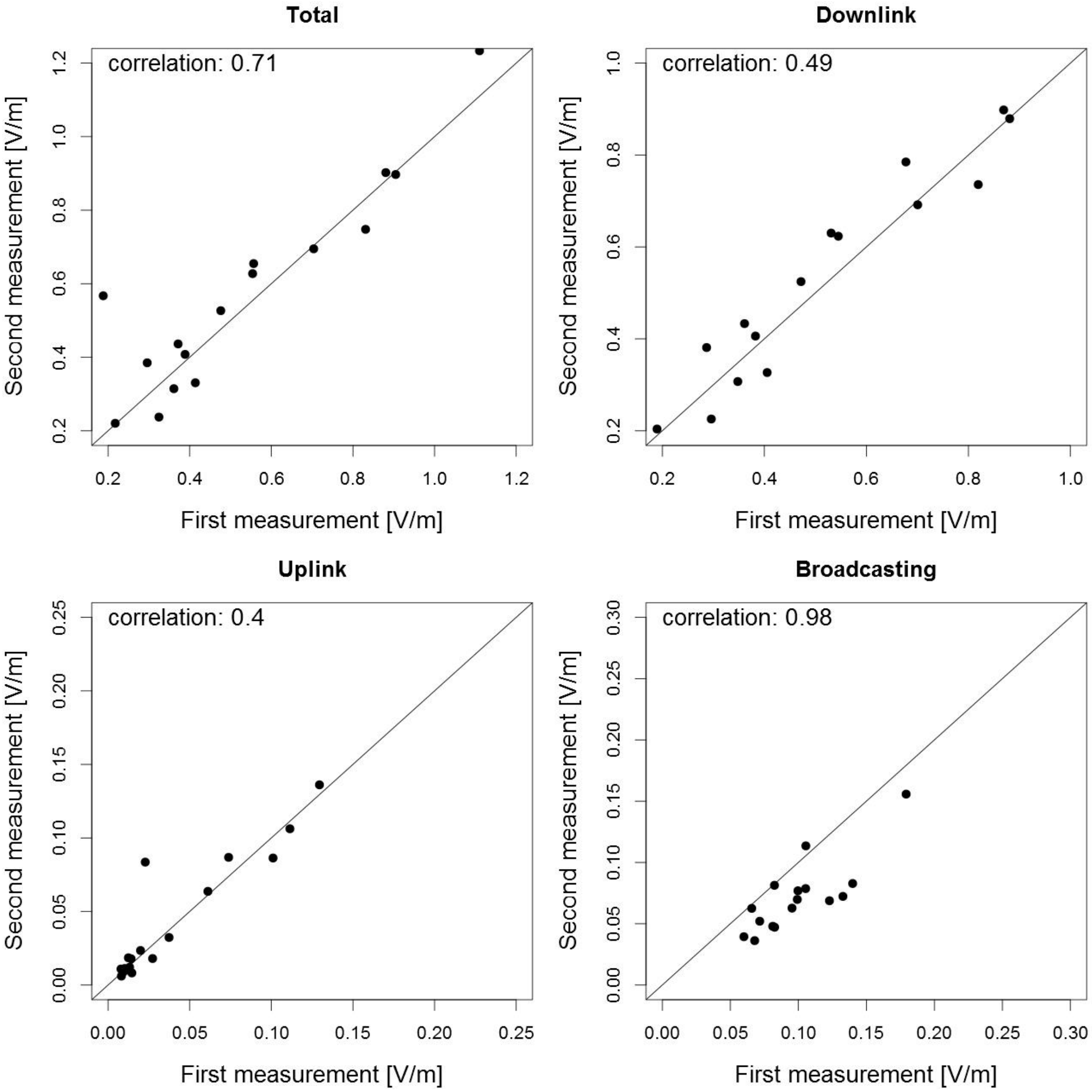

Figure S1: Spearman correlation between the first and second measurement per microenvironment in Ethiopia

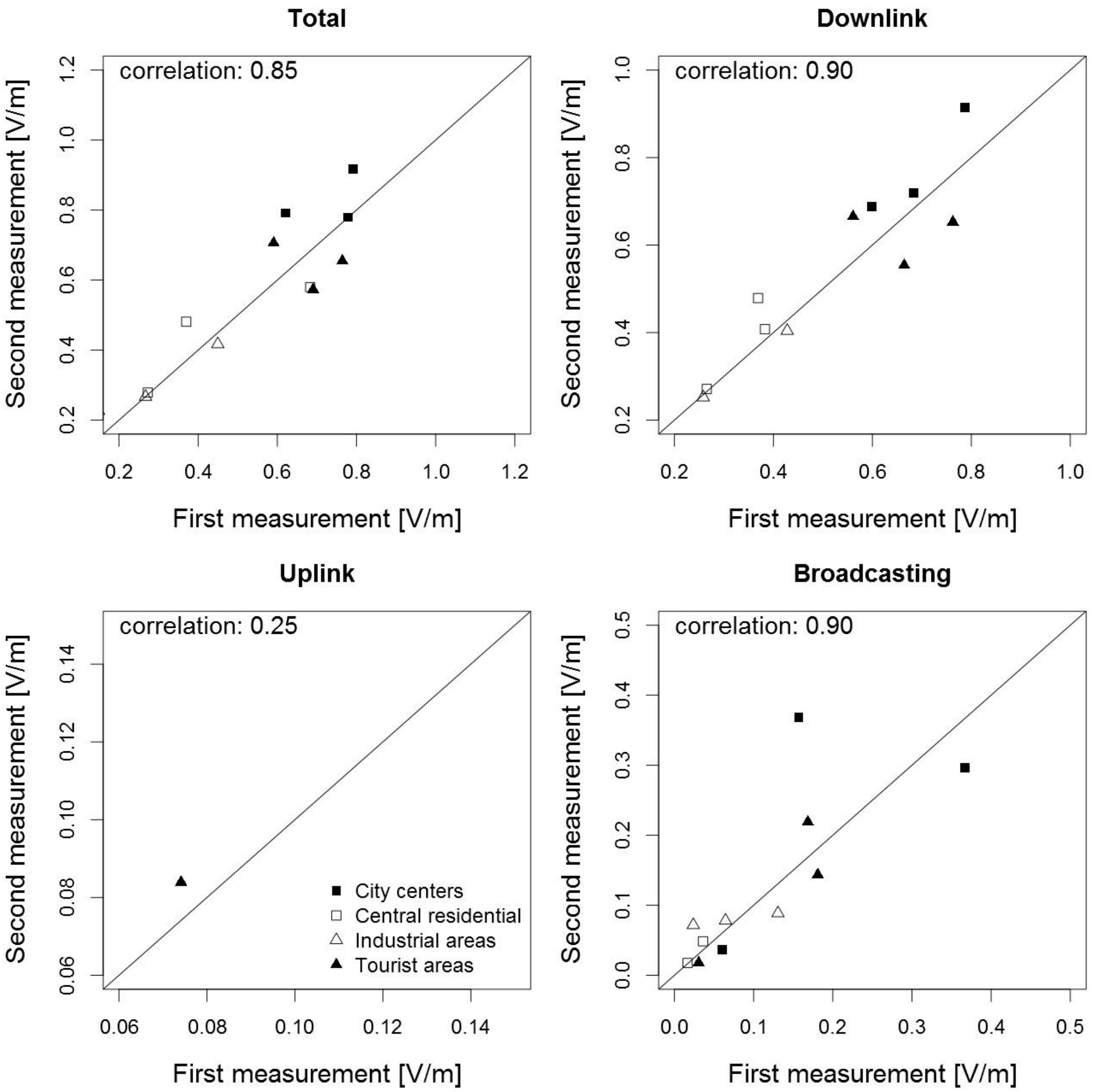

Figure S2: Spearman correlation between the first and second measurement per microenvironment in Nepal

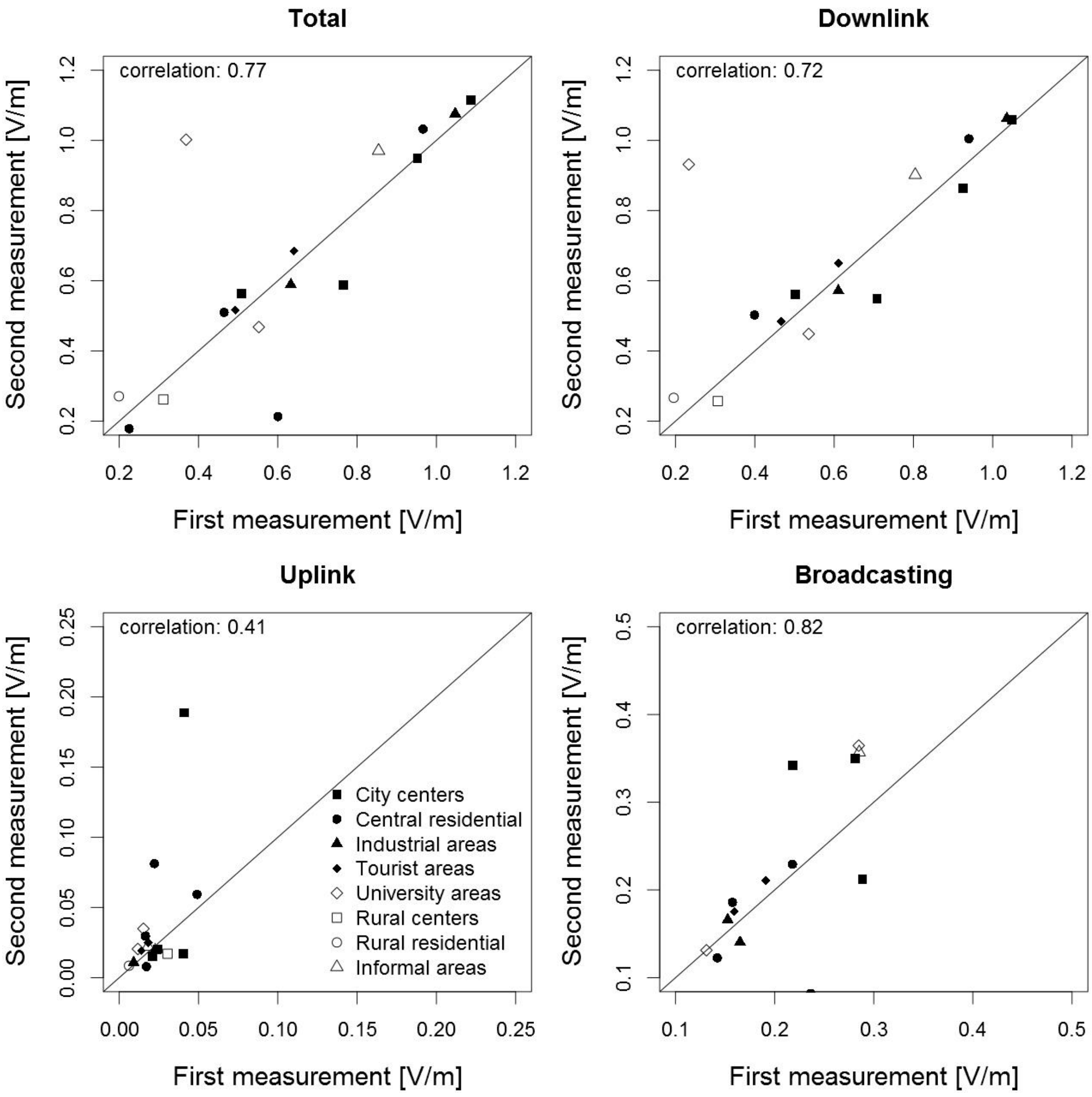

Figure S3: Spearman correlation between the first and second measurement per microenvironment in South Africa

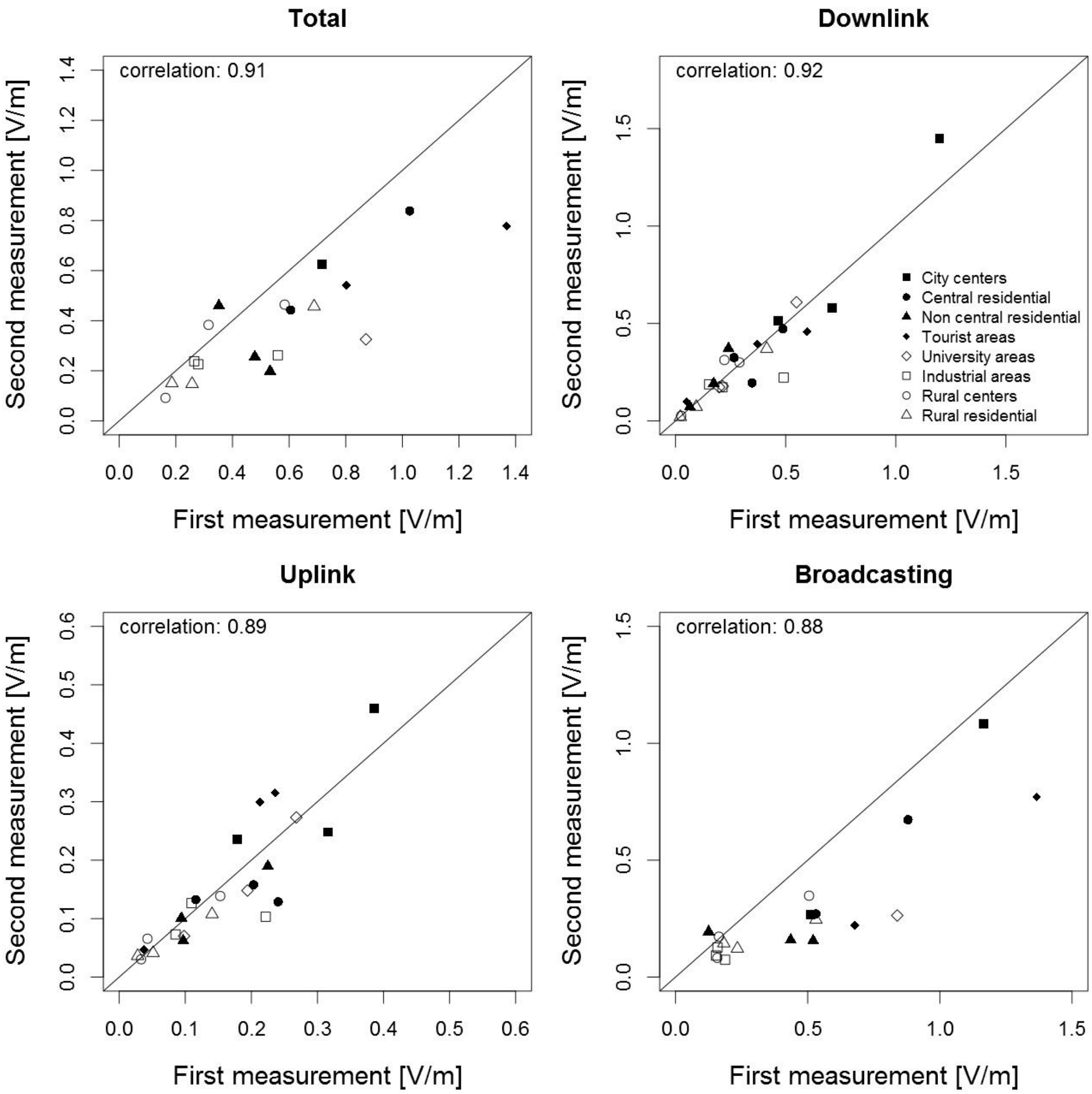

Figure S4: Spearman correlation between the first and second measurement per microenvironment in Australia

4.4.Article 4: Exposure modelling of extremely low-frequency magnetic fields from overhead power lines and its validation by measurements

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Article

Exposure Modelling of Extremely Low-Frequency Magnetic Fields from Overhead Power Lines and Its Validation by Measurements

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Abstract: A three-dimensional model for calculating long term exposure to extremely low-frequency magnetic fields from high-voltage overhead power lines is presented, as well as its validation by measurements. For the validation, the model was applied to two different high-voltage overhead power lines in Iffwil and Wiler (Switzerland). In order to capture the daily and seasonal variations, each measurement was taken for 48 h and the measurements were carried out six times at each site, at intervals of approximately two months, between January and December 2015. During each measurement, a lateral transect of the magnetic flux density was determined in the middle of a span from nine measurement points in the range of ±80 m. The technical data of both the lines as well as the load flow data during the measurement periods were provided by the grid operators. These data were used to calculate 48 h averages of the absolute value of the magnetic flux density and compared with modelled values. The highest 48 h average was 1.66 μT (centre of the line in Iffwil); the lowest 48 h average was 22 nT (80 m distance from the centre line in Iffwil). On average, the magnetic flux density was overestimated by 2% (standard deviation: 9%) in Iffwil and underestimated by 1% (8%) in Wiler. Sensitivity analyses showed that the uncertainty is mainly driven by errors in the coordinates and height data. In particular, for predictions near the centre of the line, an accurate digital terrain model is critical.

Keywords: high-voltage power lines; magnetic fields; extremely low frequency; exposure model; measurement

1. Introduction

Prolonged exposure to low-intensity, extremely low-frequency (ELF) magnetic fields (MF), such as those produced by high-voltage power lines, may have adverse effects on human health and has been a public health concern for several decades [1]. Since 1979, more than 30 epidemiological studies have scrutinized the association between childhood cancer and exposure to extremely low-frequency magnetic fields (ELF-MF) [2]. Pooled analyses combining the accumulating studies [3–5] have reported an elevated risk of childhood leukaemia associated with relatively high levels of magnetic fields exposure values from in-home measurements and calculated magnetic fields generated by overhead power lines. The strength of magnetic fields is distance dependent, and their values decrease with increasing distance from overhead power lines. Thus, several studies used distance as an exposure surrogate. For instance, Draper et al. [6] reported an increased odds ratio (OR) of 1.68 (95% confidence interval: 1.1–2.5) for childhood leukaemia among subjects living very close to overhead power lines (<50 m) compared to those residing beyond 600 m from power lines. Crespi et al. 2016 [7] reported a slight increase of cases at a distance of 50 m, with an adjusted odds ratio of 1.4 (95% confidence interval: 0.7–2.7). ORs increased very slightly for younger children (<5 years of age) and for more recent years of analysis (OR of 1.7 (95% confidence interval: 0.8–3.7) and 1.9 (95% confidence interval: 0.6–5.4, respectively). Recently, Bunch et al. 2014 [8] have re-analysed data from a previous study in relation to distance and found increased risks for children living close to overhead power lines between 1962 and 1989 but not for the later period (1990–2008). The change in the risk pattern was caused by an increase of the exposure prevalence in controls, whereas the proportion of exposed cases remained stable over time. A recent hazard assessment by the Advanced Research on Interaction Mechanisms of electroMagnetic exposures with Organisms for Risk Assessment (ARIMMORA) consortium considered the available scientific evidence published before March 2015 [9], and confirmed the previous risk assessments of IARC [10] and SCENIHR [11] that epidemiological data on the relationship of ELF-MF and childhood leukaemia is consistent with possible carcinogenicity in humans.

The epidemiological findings are relatively consistent. However, animal and toxicological studies have as yet failed to provide a biological mechanism for carcinogenicity at low exposure levels where increased childhood leukaemia risks have been observed in epidemiological studies. In addition to childhood leukaemia, there is also concern that neurodegenerative diseases [12,13] or health-related quality of life [14] may be associated with long term ELF-MF exposure from power lines.

The realization of epidemiological studies on the potential health risk from ambient ELF-MF has been hampered by the lack of a validated exposure assessment method for ELF-MF and the high cost involved with a longer time period requirement. However, the validity of exposure assessment has been an important part of studying environmental epidemiology.

The purpose of this study was to derive a model that can produce accurate long term averages of the ELF-MF from overhead lines over large areas, taking into account the diurnal and seasonal variations of the load flow for possible application in epidemiology and monitoring. Hence, a methodology and a three-dimensional (3D) computer model were developed during a pilot study in 2009 [15] and the necessary input data were identified. These data were then obtained from the electricity grid operator for a 31 km long section of the two-circuit 220 kV line Mühleberg-Bickigen/Lindenholz, for which modelling was conducted and exposure maps were calculated. In a follow-up study [16], a measurement study was carried out to validate the model at two different high-voltage overhead power lines by comparison to measured ELF-MF profiles orthogonal to the overhead lines. The model's development and validation has also been motivated by the planned national monitoring of non-ionising radiation for Switzerland. Such monitoring has already been approved by the federal government; however, its implementation is on hold as funding is not yet secured.

2. Materials and Methods

2.1. Model

2.1.1. Calculation Methods

The aim of the model was to calculate a long term time average of the magnitude of the magnetic flux density $|\vec{B}|$, e.g., an annual average using the actual line geometry and the actual operational parameters of the line.

The physical properties that enter into the calculation of magnetic fields are the current density $\vec{J}$, the magnetic vector potential $\vec{A}$, the magnetic flux density $\vec{B}$, and the magnetic field constant μ_0. The vector potential can then be calculated [17] from

$$\vec{A}(P_1) = \frac{\mu_0}{4\pi} \int \frac{\vec{J}(P_2)}{r_{12}}\, \mathrm{dV}_2 \tag{1}$$

where $\vec{A}(P_1)$ is the vector potential in point P_1, $\vec{J}\,(P_2)$ is the current density in point P_2, and r_{12} is the distance between points P_1 and P_2. The integration is carried out over all space. The magnetic flux density can then be calculated as the curl (a vector differential operator) of the vector potential

$$\vec{B} = \nabla \times \vec{A}. \tag{2}$$

The magnetic field is hence calculated from an integral over the distribution of current densities in space (i.e., in the conductors) and the distance between current-carrying conductors and P_1.

For simple geometries, e.g., thin, straight wires, the integral in Equation (1) can be solved analytically [17]. In the model, the geometry of the conductors is approximated as a collection of short linear segments; the resulting field is the sum of the contributions from all the segments. For each conductor segment, the magnetic field contribution is proportional to the current I, which is the integral of the current density over the cross-section of the conductor.

The magnetic fields are three-dimensional vectors; the currents as well as the vector components have magnitude and phase. The appropriate mathematical entities to deal with such properties are complex-valued vectors.

The main input data for the modelling are geometric data and load flow data.

2.1.2. Load Data

Load flow data, including magnitude, phase, and load flow direction for each current circuit, are needed to calculate the active current I_a and reactive currents I_r. The load flow data are recorded by the operators of the electricity grid, typically as time, voltage U (in kV), active power P (in MW), and reactive power Q (in MVAR). The calculation is done as following:

$$P + iQ = \sqrt{3}\, U\, I^* = \sqrt{3} U\, (I_a - i\, I_r) \tag{3}$$

for a symmetrical three-phase system, where the asterisk * denotes complex conjugation and i the imaginary unit.

The currents show strong daily and seasonal variations. On lines with multiple circuits, they are in general different on different circuits, they can change direction, and also the relative directions between circuits can change from same-direction to opposite. This is illustrated by the data from the pilot study shown in Figure 1 for the range of current variations over an entire year and in Figure 2 for the variations over a 48-h period.

The resulting field at any location is the vector sum of the contributions of the different circuits. Depending on the geometry, the phase assignment, and the varying relative directions of the load flow, the fields can either amplify or partly compensate.

Since the temporal variation of the load data is high, these computations need to be done with a high temporal resolution (15–60 min). To accelerate the calculation of time averages, the load data were grouped in clusters of similar values. This grouping can be automated by a procedure called k-means-clustering [18]. The method is iterative: each cluster is represented by its centre point. Starting with a small number of clusters with arbitrary initial values, data points are assigned to the cluster with the closest centre. When all of the points are assigned, the cluster centres are updated, and, while the number of clusters is smaller than the intended number k, the cluster with the largest variance is split in two. The steps (assignment, update, and possible split) are repeated until the assignments no longer change. The algorithm always converges to a fixed point. In our implementation, the points are always assigned to clusters with the same sign in all parameters to avoid the cancellation of positive and negative values. For n circuits, the clustering is carried out in 2n-dimensions (active and reactive current for each circuit). An example plot for hourly load data from the pilot study using a clustering with k = 12 is shown in Figure 3.

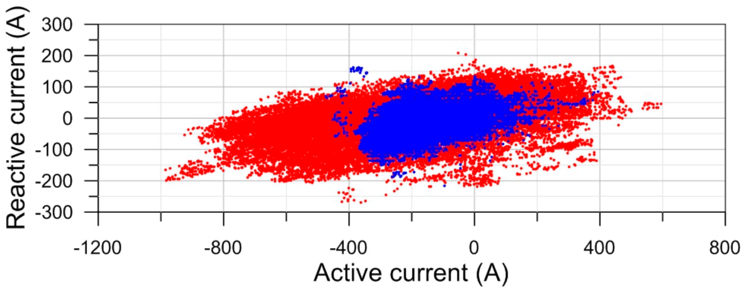

Figure 1. Scatterplot of active and reactive currents on a two-circuit 200 kV/132 kV line, 15 min averages for one year. Red: 220 kV, blue: 132 kV. Source: report on the pilot project [15].

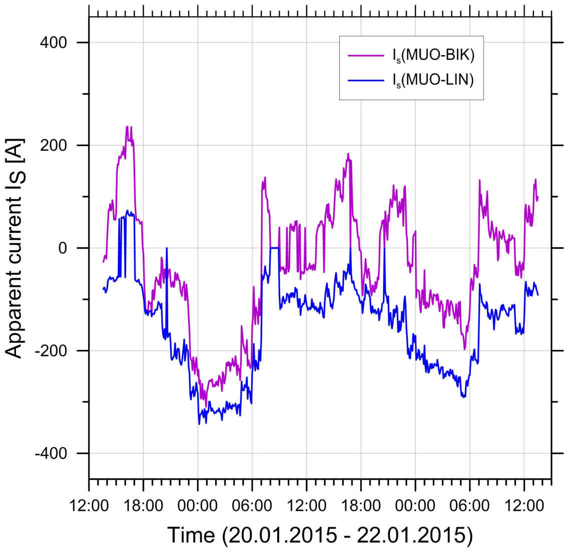

Figure 2. Daily variation of current data in two circuits of a 220 kV/220 kV line. Data from the first measurement period. The colours distinguish the two circuits. MUO-BIK, Mühleberg-Ost to Bickigen; MUO-LIN, Mühleberg-Ost to Lindenholz.

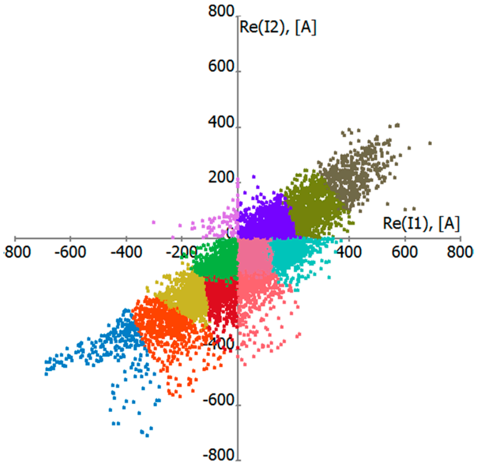

Figure 3. K-means-clusters for a 2 × 220 kV line with k = 12 clusters. Projection of the clusters on the plane of the active currents (i.e., real part of complex current). Points belonging to different clusters are distinguished by different colours.

2.1.3. Geometric Data

The geometric data describe the position of the towers and their geometry, i.e., the lateral and vertical position where the conductors are attached (as shown in Figure 4), the line sag between towers, the phase arrangement of the conductors, and finally one also needs the topographical data of the area surrounding the line in the form of a digital terrain model.

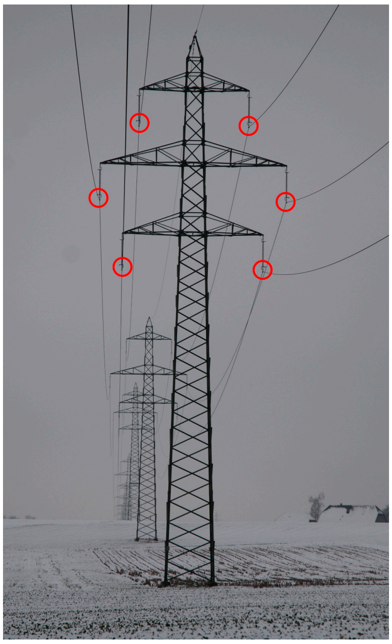

Figure 4. Position of the conductors on the tower, case of the 2 × 220 kV line in Iffwil. The position of the attachment point is determined by the position and geometry of the tower and the length of the isolators.

Of the geometric data, only the line sag and lateral displacement by wind are variable in time. Line sag depends on a number of properties (weight, elasticity, thermal expansion coefficient, and tensile stress), the temperature, the span between towers, and added load (e.g., ice, wind). The conductor temperature depends on Ohmic heating by the current, the meteorological conditions (air temperature, wind and solar irradiation), and radiative cooling. The maximum sag is found at the maximum conductor temperature (maximum current) or the maximum added load. Under most circumstances, the currents are smaller and the cooling more efficient than in the maximum sag case, which means that the temperature is not much higher than the air temperature (this would no longer be true if the line is operated near its maximum capacity or in case of so-called high-temperature conductors, these cases would have to be treated differently). For the lines under study, with spans of approx. 300 to 400 m between towers, the sag, as given by the tables of Swissgrid and Bernische Kraftwerke (BKW), varies by only about ±1 m for a temperature variation of ±30 °C (i.e., between −20 °C and +40 °C), and thus a constant approximate value is applied in the model, which makes the sag, and therefore the line geometry, independent of the time interval. Lateral displacement by wind is neglected in the model.

Figure 5 shows in an exemplary way the effects of line sag and topography for the pilot study modelling [15]. Elevated field strengths are found only in narrow corridors around the power line, and are typically highest in the middle between two towers.

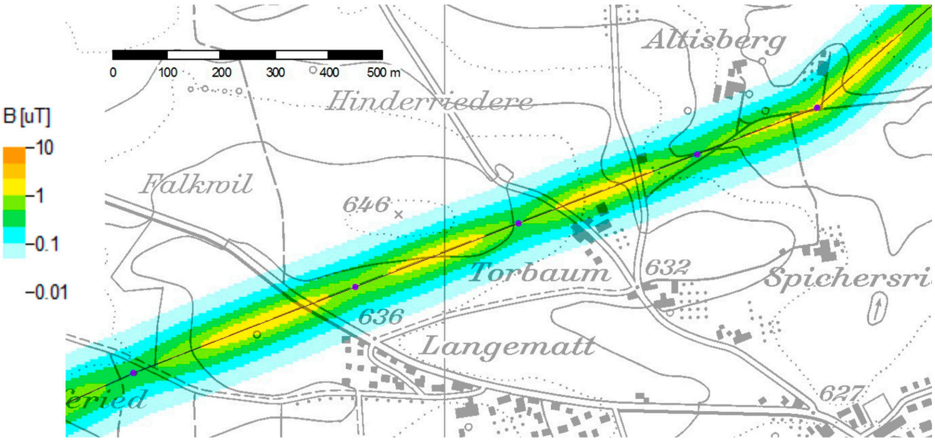

Figure 5. Detailed result of a color-coded magnetic field map produced in the pilot project. Background map PK25 © Swisstopo.

2.1.4. Error Estimates and Simplifications

In this section, some error estimates will be made based on a simple two-dimensional approximation, and some possible simplifications will be discussed based on these estimates.

The field of a single thin, straight, infinitely long conductor is given as

$$B = \frac{\mu_0 I}{2\pi r}. \tag{4}$$

Here, I is the current and r is the distance from the conductor. For a circuit of three-phase conductors, the corresponding field strength is approximately, for $r \gg g$

$$B = \frac{\mu_0}{2\pi} \frac{Ig}{r^2} \tag{5}$$

where g is a geometry factor which has the dimension of length. It represents the mean distance between the conductors, which depends on the geometrical arrangement of the conductors. Example values for various configurations can be found in the Electric Power Research Institute (EPRI) "red book" (Table 7.4.3 of [19]).

Directly under a line, the field is most strongly influenced by the lowest conductor, and the distance is approximately $r \approx h$, i.e., the height of the lowest conductor. Then, the field is approximately given by (4), and the uncertainties δB and δh are related by

$$\frac{\delta B}{B} \approx \frac{\delta h}{h}. \tag{6}$$

In this case, an error of 1 m for a line at height 10 m would give a relative error of 10% in both h and B. At larger horizontal distances from the line centre, the field of a three-phase circuit scales as in Equation (5), with the distance r approximately equal to the horizontal distance. As the field scales as $1/r^2$, an error δr in distance produces an error of the field

$$\frac{\delta B}{B} \approx 2\frac{\delta r}{r} \tag{7}$$

hence, a 10% position error of 5 m at distance 50 m would lead to a 20% error in the magnetic field. Large positional errors could possibly occur in epidemiological studies when home addresses are converted into coordinates, as has also been noted in [20].

For a double-circuit line and towers as in Iffwil or Wiler, different phase arrangements of the two circuits are possible, and the two most common configurations are shown in Figure 6.

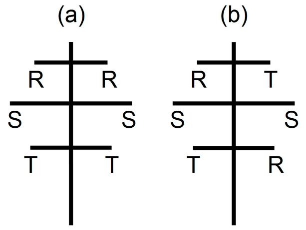

Figure 6. Two common phase arrangements for a standard 220 kV or 380 kV tower, for phases designated R, S, and T. (**a**) plane symmetry; (**b**) central symmetry. Four other, intermediate configurations are also possible, but not shown here.

The field for a line of two circuits at horizontal distance d and phase arrangement as in Figure 6 (or any permutation of R, S, T) can be approximated as

$$B \approx \frac{\mu_0 g}{2\pi}\left(\frac{I_1}{{r_1}^2} \pm \frac{I_2}{{r_2}^2}\right). \tag{8}$$

The plus sign applies to configuration (a), the minus sign to configuration (b) of Figure 6. Assuming equal currents $I_1 = I_2 = I$ in both circuits, setting $r_{1,2} = r \mp d/2$, and expanding the expression w.r.t. $1/r$, one obtains

$$B_p \approx \frac{\mu_0 g}{\pi}\frac{I}{r^2} \qquad (\text{configuration a, plane symmetry, } r \gg d \tag{9}$$

and

$$B_c \approx \frac{\mu_0 g d}{\pi}\frac{I}{r^3} \qquad (\text{configuration b, central symmetry, } r \gg g, d). \tag{10}$$

Depending on the phase arrangement, the magnetic field falls off either as r^{-2} or as r^{-3}. In the first case, the magnetic fields of the circuits add up and roughly double the field; in the second case, they partly compensate and the field falls off much faster with distance. The ratio of the two field expressions with different phase symmetry is

$$r = B_p/B_c \approx \frac{r}{d} \qquad (r \gg d). \tag{11}$$

Hence, for a typical 220 kV line with $d \approx 10$ m, at 50 m distance from the line the two Expressions (9) and (10) would differ by a factor of 5. In the case where the currents in the two circuits are equal and opposite (i.e., opposite load flow directions), the role of the two-phase arrangements reverses, and the fields compensate for configuration (a) and add for configuration (b).

Figure 6 and Equations (8)–(11) illustrate the difficulty of modelling magnetic fields for lines with more than one circuit. Not only is it mandatory to know the phase arrangement, but also the currents and both load flow directions must be known, since a false arrangement or load flow sign could lead to large errors, as in Equation (11). The situation becomes even more complex if currents vary in time and load flow directions change, as shown, e.g., in Figure 2, especially if they also change from parallel to antiparallel. For this reason, it is very difficult to make simple approximations for magnetic field calculations for lines with two or more circuits, except in simple circumstances.

2.1.5. Computations for Validation

The model was applied to the two different measurement sites to calculate 48 h ELF-MF for each measurement period. For these calculations, the following data were obtained and used for the modelling:

- List of the coordinates of tower positions x and y (and later also z)
- Mast-schemas for all masts, one drawing per mast
- Drawings of isolators
- Phase-allocation schema for all circuits
- Graphics/tables on line sag, for all spans
- Load flow data (time, voltage, active power, and reactive power) as 15 min averages for the measurement periods and 1 h averages for the whole year 2015 from Swissgrid and in part also from BKW.
- Two different digital terrain models: (1) the DHM25 with 25 m resolution, and (2) the more precise model DHM5 with 5 m resolution.

For the calculation of the active current I_a and reactive current I_r, we used a clustering with k = 16, which was demonstrated in the pilot study [15] to be sufficiently accurate: for the relevant heights of 10 to 20 m below the lowest conductor and all lateral distances, the relative errors were in the range of ±2%. Larger errors (up to 5%) only occurred in the near region between the conductors. The effort could even be reduced further by using root-mean-square (RMS) averages, as detailed in [16]. For comparison, these RMS averages were also calculated for the validation study.

The following approximations were therefore used for the model calculations. First, the currents are assumed to be symmetric, all phases of a circuit have the same amplitude, and the phases are shifted by exactly 120°. No account was taken of currents induced in the earth or the shield wires, nor of unbalanced currents induced in the circuits. Second, the line sag was assumed to be the line sag at 10 °C, close to the average air temperature (9 °C in the Swiss plateau).

Unless the terrain is absolutely flat, which at least in Switzerland is seldom the case, a numeric terrain model must be used to derive the height of tower bases and the height of receptor points. Two different such models were used. First, we used a relatively coarse grid of 25 m resolution (DHM25). Such grids are readily available almost everywhere, and they require small storage space and come at a low cost; however, their precision is limited. Second, we used a higher resolution (5 m) grid (DHM5). Higher resolution grids are more precise, but they come at a larger cost and may not be available everywhere.

Four different variants of the model were calculated for the comparison with the measurements, differing by the type of temporal average calculated and the precision of the terrain model:

- Model A: gives the arithmetic average $\overline{B}$ using the 25 m resolution terrain model DHM25.
- Model B: gives the RMS mean B_{RMS} using the 25 m resolution terrain model DHM25.
- Model C: gives the arithmetic average $\overline{B}$ using the 5 m resolution terrain model DHM5.
- Model D: gives the RMS mean B_{RMS} using the 5 m resolution terrain model DHM5.

The arithmetic mean $\overline{B}$ of the absolute value of the magnetic flux density $|\vec{\boldsymbol{B}}_i|$ for n time periods was computed as the following:

$$\overline{B} = \frac{1}{n} \sum_{i=1}^{n} |\vec{\boldsymbol{B}}_i| \tag{12}$$

and the root-mean square B_{RMS} as

$$B_{\mathrm{RMS}} = \left(\frac{1}{n} \sum_{i=1}^{n} |\vec{\boldsymbol{B}}_i|^2 \right)^{1/2}. \tag{13}$$

There exists a simple relation between the two means, which follows directly from the definition of the variance:

$$B_{\mathrm{RMS}}^2 = \overline{B}^2 + \frac{n-1}{n}\,\sigma_B^2 \tag{14}$$

where σ_B^2 is the variance of the $|\vec{\boldsymbol{B}}_i|$.

When calculating averages as $\overline{B}$ or B_{RMS}, one must keep in mind that the original measurements themselves always represent RMS values, as the arithmetic mean over a sinusoidally varying quantity is zero and only an RMS value is meaningful. The difference in the averaging procedure applies only to the averaging over the set of larger time periods (e.g., 15 min or 1 h values).

The calculations were carried out with an ad hoc modified version of the NISMap-software (NISMap-ELF) developed by ARIAS.

2.2. Measurements

2.2.1. Selection of Sites for Validation

The aim of the validation study was to validate the model by measuring at two different sites below two different overhead power lines. The first site was in Iffwil, approximately 13 km North-North East of Bern. The site is below the 2 × 220 kV line that had already been the subject of the pilot study. The line is operated by Swissgrid (during the pilot study it was still operated by BKW); it connects Mühleberg-Ost (MUO) to Bickigen (BIK) and Lindenholz (LIN). The line has single conductors (per phase), and the height of the lowest conductors above ground is approximately 12 m (at 10° conductor temperature). The second site was in Wiler bei Seedorf, approximately 15 km Northwest of Bern, below a 220 kV/132 kV line operated by Swissgrid (the 220 kV circuit) and BKW (the 132 kV circuit), connecting Mühleberg-Ost (MUO) to Pieterlen (PIE, 220 kV) and Kappelen (KAP, 132 kV). The geometry of the towers is as for a 380 kV line. The towers of the line are symmetric, but the 220 kV line has a bundle of four conductors and the 132 kV line a bundle of two conductors. As the tower to the north of the site is situated at the edge of a wood, it is much higher than the southern one, and the minimum ground distance of the conductors is to the south of the measurement site. Consequently, the ground distance of the lowest cables is higher in Wiler, with a nominal 20.8 m (220 kV) and 19.5 m (132 kV) at 10 °C. The differences are due to different isolator lengths and the inclination of the terrain. Both sites are in rural settings on agricultural paths where very few people pass. The measurements were made along the agricultural paths, which pass below the power line at near right angles (84.6° in Iffwil, 68.5° in Wiler). Maps of the sites and the measurement points are shown in Figure 7.

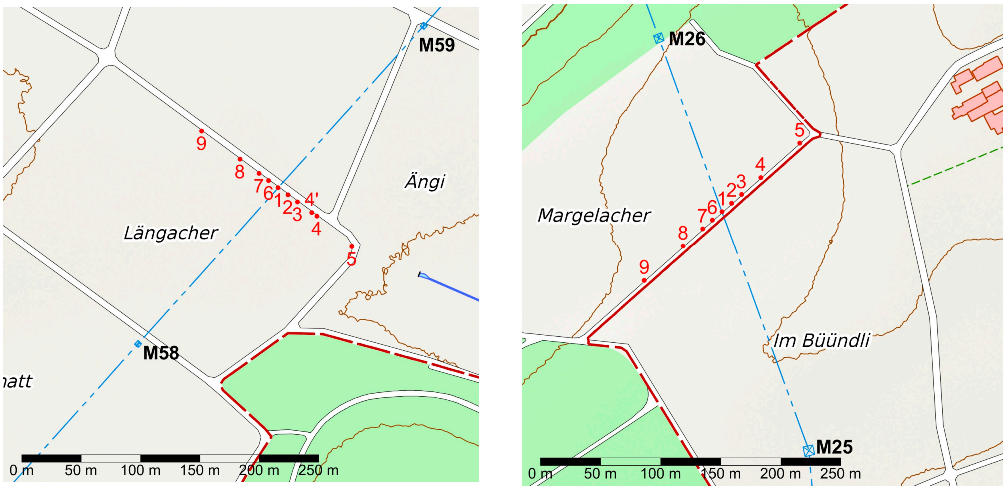

Figure 7. Measurement sites in Iffwil (**left**) and Wiler (**right**). The blue dash-dotted line marks the power line axis between the towers; the nearest towers are marked M58/M59 and M25/M26, respectively. The red points mark the measurement points, numbered 1 to 9. Measurement point 1 is below the line axis, points 2 to 5 are on one side, and 6 to 9 on the other side of the axis. The red lines mark boundaries between municipalities. Background map data AV, © Swisstopo.

2.2.2. Measurement Procedures

To capture daily variations, each measurement lasted for 48 h during each measurement period. To capture seasonal variations, measurements at each site were repeated approximately every two months during one year. This resulted in a total of 12 measurement periods, six each at each measurement site (Iffwil and Wiler), in the period between January and December 2015. The measurements were carried out during the week, typically from Tuesday to Thursday (only one period was from Wednesday to Friday, in the week after Easter). The measurement periods are listed in Table 1. The measurements typically started around noon, somewhat earlier in summer to avoid the heat, and somewhat later in fall and winter to avoid the morning fog.

Table 1. Measurement periods at the two sites. "Begin" and "End" mark the times of the 48 h of data used for the evaluation.

Measurement Nr.	Site	Begin	End
M1	Iffwil	20 January 2015 13:30	22 January 2015 13:30
M2	Wiler	17 February 2015 14:00	19 February 2015 14:00
M3	Iffwil	24 March 2015 12:30	26 March 2015 12:30
M4	Wiler	8 April 2015 12:30	10 April 2015 12:30
M5	Iffwil	26 May 2015 14:00	28 May 2015 14:00
M6	Wiler	2 June 2015 14:00	04 June 2015 14:00
M7	Iffwil	7 July 2015 10:30	9 July 2015 10:30
M8	Wiler	28 July 2015 11:00	30 July 2015 11:00
M9	Iffwil	8 September 2015 12:30	10 September 2015 12:30
M10	Wiler	15 September 2015 13:00	17 September 2015 13:00
M11	Iffwil	27 October 2015 13:15	29 October 2015 13:15
M12	Wiler	8 December 2015 14:00	10 December 2015 14:00

Measurement devices were placed in a lateral transect at orthogonal distances $D = 0$, ±10 m, ±20 m, ±40 m, and ±80 m from the centre of the line. This profile was located approximately in the middle of a span. The magnetic field measurement devices were placed at approximately 10 cm above ground.

It was ensured that no other electricity lines or communication cables were located in the vicinity of the measurement points. However, in Iffwil, the village brook is flowing in a duct underneath the measurement path, and one of the points in Iffwil (Point 4) was very near to a manhole cover of this village brook. During the setup for the first measurement period, the ground was snow-covered and the manhole had remained unnoticed. The cover was of cast-iron and concrete. Due to this, the point was shifted by 5 m (to Point 4) after the first measurement. The magnetic field measurement devices were the following:

- Emdex II. Seven devices were placed at distances 0 to ±40 m.
- Estec DL-MW10s. One device was placed at distance 0 m together with an Emdex II, and a second one was used as a spare and for spot measurements.
- Estec EMLog2e. Two devices were placed at ±80 m, as they have higher sensitivity and resolution than the Emdex II and DL-MW10s.

The technical data of the devices are given in Table A1 of Appendix A. The parallel measurements of the EMDEX II and Estec devices agreed to within 2% in Iffwil and 0.5% in Wiler, on average, corresponding well with the indicated precision (3%) specified for both types of devices. The Emdex devices had been repeatedly calibrated in a previous measurement campaign [21] and found to be very stable. The Estec devices were new and had been calibrated by the manufacturer.

All magnetic field measurement devices are specified for positive temperatures only (0 °C to 60 °C for the Emdex devices and 0 °C to 40 °C for the Estec devices). In order to protect them from temperatures outside the specified range, they were placed in thermally isolating boxes (of expanded polystyrene, EPS) and thermally buffered with a phase-change material (PCM) with a phase transition at 5 °C. The PCM used was PX05 (manufacturer Rubitherm, www.rubitherm.com), which is composed of a mixture of paraffin and water embedded in an inorganic matrix. It comes in the form of a crystalline powder, is chemically inert, nonconducting, and nonmagnetic. Some 325 g of PX05 were placed in every measurement box. In order to verify that the temperature in the boxes remained indeed in the allowed range, temperature loggers (Rotronic TL-1D) were used in two of the boxes. The measurement boxes were protected against the weather with additional plastic covers and fixed to the ground with plastic straps. All materials used were nonmetallic, nonconductive, and nonmagnetic. The setup of the measurement boxes at both sites is shown in Figure 8.

Figure 8. Measurement setup with the (white) measurement boxes in Iffwil (**left**) and Wiler (**right**). Only the right image shows the entire length of the measurement path with all nine boxes. Also shown in the left picture is the target table that was used with the laser distance meter to position the boxes and to measure the height to the conductors.

3. Results

3.1. Pilot Study

The results of the feasibility and pilot study [15] were the identification of the necessary input data and the development of the methodology to calculate long term averages of the magnetic field. An estimate of the work effort required for the data acquisition resulted in at least 4.5 to 6 work hours for an equivalent line of some 30 to 40 km length with some 100 towers once the basic model is set up and the contact to the grid operator established. With some 100 such lines in the Swiss transmission system (220 kV and 380 kV lines), this would already result in a considerable effort for a complete exposure map. Compared to this, the actual computational effort on the computer is negligible.

Finally, an error estimate was performed and the precision of the results estimated to approximately 10 to 25%. The largest errors result from uncertainties in the coordinates, i.e., the x-y-coordinates, the height (both of conductors and terrain), and the line sag.

3.2. Modeling

For every measurement period, the load flow data were obtained from the grid operator and the currents were calculated. Examples of the typical behaviour of the currents on the two circuits are shown in Figure 9 for measurement periods M2 and M4 in Wiler. During both periods, a high correlation of the currents in the two circuits is visible. The figure also shows the peaks that occur at certain daytimes. Also visible from the figure is the change in the currents' sign (i.e., the change in the direction of load flow), but also that the currents in the two circuits sometimes have the same sign (most of the time during M2), but sometimes also have opposite signs (most of the time during M4).

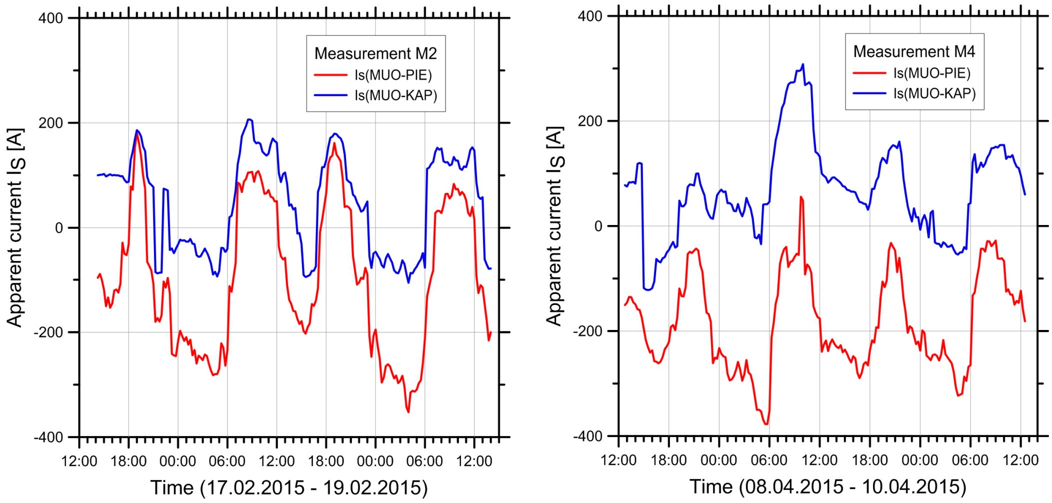

Figure 9. Plots of the apparent current I_S in the two circuits MUO-PIE (Mühleberg-Ost to Pieterlen) and MUO-KAP (Mühleberg-Ost to Kappelen) during measurement periods M2 (**left**) and M4 (**right**) in Wiler.

3.3. Measurements

For each measurement period, a time series of the magnetic field at each measurement point was collected. An example, for measurement M5, is shown in Figure 10. The magnetic flux densities range from maxima of around one to a few µT near the line axis down to less than 10 nT at the outermost measurement points. The curves on the two sides of the line centre (positive vs. negative distances) show somewhat different behaviour, reflecting different loads on the two circuit systems.

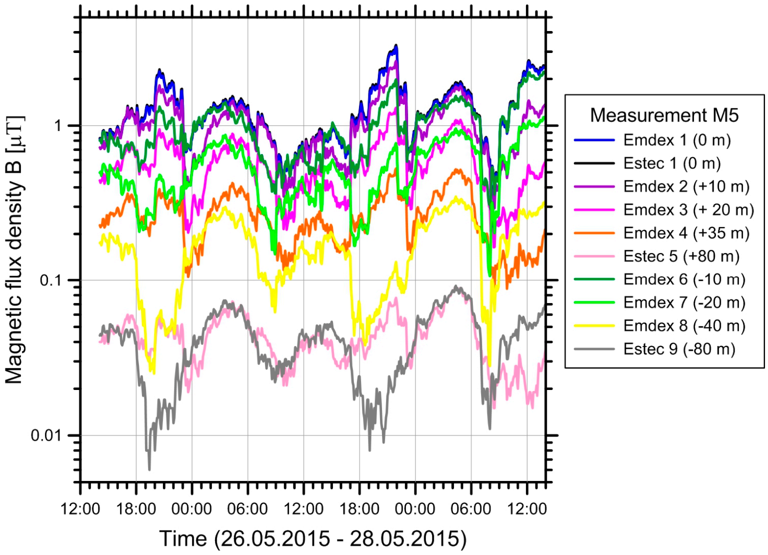

Figure 10. Measured magnetic fields during measurement M5 for all devices. The devices Emdex 1 and Estec 1 were measuring at the same measurement point and the curves of these devices are indistinguishable in the figure.

Figure 11 shows an example of a temporal pattern between the apparent currents I_S in the two circuits and the magnetic fields measured at ±10 m from the measurement period M9. It is visible that the magnetic field follows closely the current on the nearer circuit, at least as long as one of the currents is dominant.

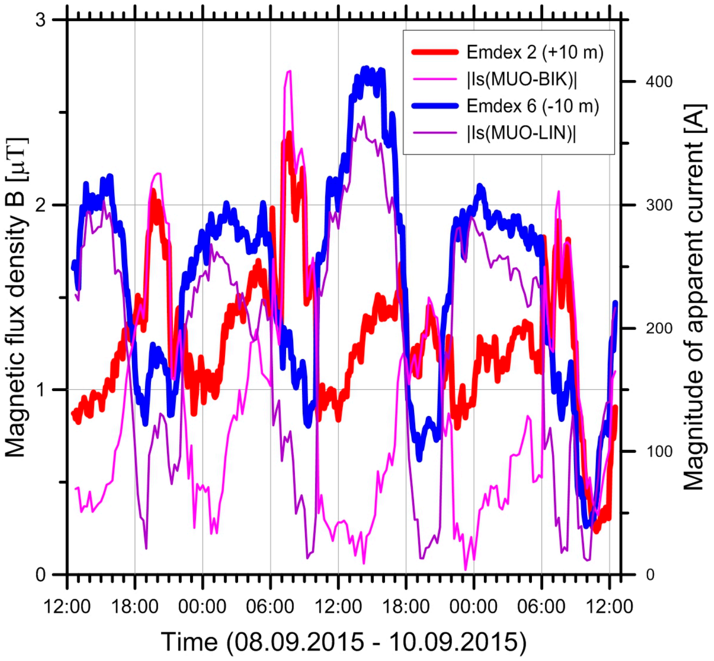

Figure 11. Magnitude of apparent current in the two circuits MUO-BIK and MUO-LIN and magnetic fields measured at ±10 m (Emdex 2 and Emdex 6, measurement M9 in Iffwil). Emdex 2 measures on the side of MUO-BIK, Emdex 6 on the side of MUO-LIN.

3.4. Comparison between Measurements and Modelling

The comparison of the measured magnetic arithmetic means $\overline{B}$ and Models A and C is shown in Figure 12 for two of the measurement periods. It can be seen that the Model C based on the more precise digital terrain model DHM5 (5 m resolution) yields better agreement for the points near the line axis compared to Model A (DHM25). For measurement points further away from the centre line (>30 m), the two models provide nearly the same results. The difference between the two models is more pronounced in Wiler, since one of the towers is standing on a ridge. This made the interpolation with the DHM25 imprecise. The height of the conductors above the path, as derived from the numerical terrain model, was different by about two meters between the two models. Measurements with a LASER distance-meter revealed that the DHM5 model provided correct values for the distances of the conductors above ground, but the DHM25 model did not. In the case of measurement M9, the largest relative deviations between model and measurement occurred at the largest distances (±80 m).

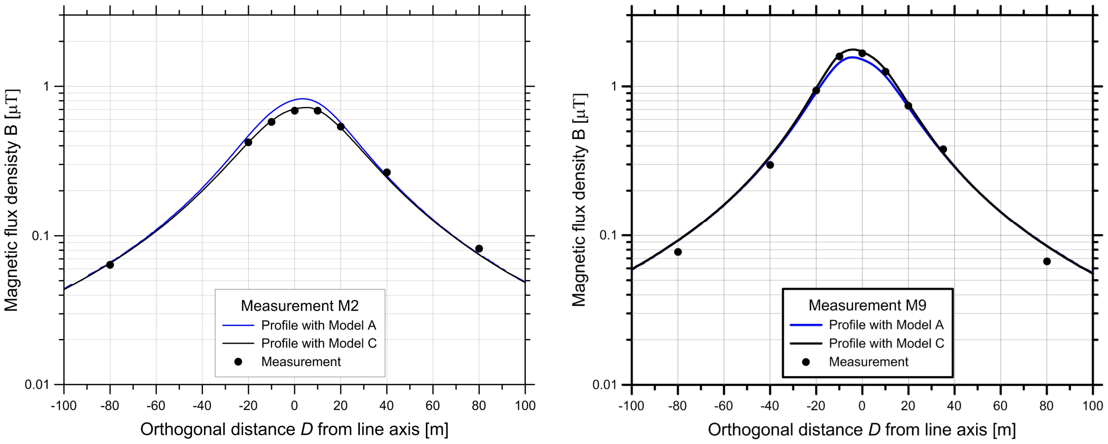

Figure 12. Comparison of the modelled lateral profiles for two measurements. (**Left**) M2 in Wiler; (**Right**) M9 in Iffwil. The dots are the measurements, and the lines are the calculated values for two different numerical height models: Model A uses the DHM25 (blue curves), Model C uses the more precise DHM5 (black curves).

The measured and calculated time averages for all measurement periods and all measurement points are given in the tables of the supplementary material.

Statistical Evaluation of Model Uncertainty

As the magnitude of the measured values varies by orders of magnitude between near and far points, it is reasonable to analyse the relative deviation between model and measurement, defined as

$$\Delta \ := \frac{B\ (\text{model}) - B(\text{measured})}{B(\text{measured})}. \tag{15}$$

Depending on the model, B is the arithmetic mean $\overline{B}$ (Models A and C) or the RMS mean B_{RMS} (Models B and D). The results are given as mean $M(\Delta)$ (offset) and standard deviation $\sigma(\Delta)$ for all measurement points at a measurement site and a given model variant; they are tabulated in Table 2.

On average, Model A underestimates the magnetic fields in Iffwil by 4% (standard deviation SD: 11%) and overestimates them in Wiler by 7 to 8% (SD: 8%). According to Model C, the mean deviation in Iffwil was 2% (SD: 9%) and in Wiler 1% (SD: 8%) (Table 2). Independent of the terrain model used, the results for the relative deviation Δ are very similar for $\overline{B}$ or B_{RMS} (Model A vs. Model B and Model C vs. Model D).

Table 2. Mean $M(\Delta)$ and standard deviation $\sigma(\Delta)$ of the difference between model and measurements for the models with the DHM25 (Models A and B) compared to those with the DHM5 (Models C and D).

		Iffwil		**Wiler**	
		M **(Δ)**	σ **(Δ)**	M **(Δ)**	σ **(Δ)**
Model A (for $\overline{B}$)	DHM25	−0.04	0.11	0.07	0.08
Model B (for B_{RMS})		−0.04	0.11	0.08	0.08
Model C (for $\overline{B}$)	DHM5	0.02	0.09	−0.01	0.08
Model D (for B_{RMS})		0.02	0.09	−0.01	0.07

The three most pronounced discrepancies between model and measurement (in terms of Δ) were found to be −28% (M1), +27% (M9), and +29% (M8). Underestimation of the model by 28% occurred during the first measurement period M1 in January 2015 in Iffwil for the measurement point at D = +40 m. This measurement point was close to a manhole cover made of cast-iron and concrete, as described in the methods section. As a consequence, the measurement point was moved by 5 m to D = +35 m for the later measurements.

The other large discrepancies between model and measurement occurred at the most distant measurement points at $D = \pm 80$ m in Iffwil (M9) and Wiler (M8).

To explore the relative deviation between model and measurement in relation to distance from the centre of the line, the data points were divided into two groups: "Near points" are the innermost three with orthogonal distances D = 0 and ±10 m; "far points" are the outer four at distances between 35 m and 80 m. For the Models A and B based on DHM25, the offset $M(\Delta)$ is considerably larger for near points than for far points at both measurement locations (Table 3). However, the opposite pattern is seen for the standard deviation between model and measurement. With the more precise terrain model used in Models C and D, the mean error $M(\Delta)$ for near-axis points becomes markedly smaller for both measurement locations (Table 4). For distant points, improvements compared to Models A and B are mainly seen in Wiler. The standard deviation is little affected by the choice of the terrain model, except for near points in Iffwil, where a reduction of the standard deviation is observed.

Table 3. Statistics (mean $M(\Delta)$ and standard deviation $\sigma(\Delta)$) of the difference between model and measurement, separately for near and far points for models with the DHM25.

	Near Points, $\lvert D\rvert \leq 10$ m				**Far Points, $\lvert D\rvert \geq 35$ m**			
	Model A (for $\overline{B}$)		**Model B (for B_{RMS})**		**Model A (for $\overline{B}$)**		**Model B (for B_{RMS})**	
Site	$M(\Delta)$	$\sigma(\Delta)$	$M(\Delta)$	$\sigma(\Delta)$	$M(\Delta)$	$\sigma(\Delta)$	$M(\Delta)$	$\sigma(\Delta)$
Iffwil	−0.11	0.08	−0.12	0.07	0.03	0.13	0.03	0.12
Wiler	0.11	0.05	0.12	0.05	0.05	0.10	0.05	0.09

Table 4. Statistics (mean $M(\Delta)$ and standard deviation $\sigma(\Delta)$) of the difference between model and measurement, separately for near and far points for models with the DHM5.

	Near Points, $\lvert D\rvert \leq 10$ m				**Far Points, $\lvert D\rvert \geq 35$ m**			
	Model C (for $\overline{B}$)		**Model D (for B_{RMS})**		**Model C (for $\overline{B}$)**		**Model D (for B_{RMS})**	
Site	$M(\Delta)$	$\sigma(\Delta)$	$M(\Delta)$	$\sigma(\Delta)$	$M(\Delta)$	$\sigma(\Delta)$	$M(\Delta)$	$\sigma(\Delta)$
Iffwil	0.01	0.04	0.01	0.04	0.03	0.12	0.04	0.12
Wiler	−0.03	0.05	−0.03	0.05	0.02	0.09	0.02	0.09

4. Discussion

The validation study has shown that the time-averaged magnetic field can be modelled with relative precision in the percent range.

Both the measurement, and, given the necessary input data, the computation of magnetic fields from overhead power lines are in principle straightforward, and the measurements and calculations generally agree well. An example with very detailed input (currents measured on individual phases and the shield wire) was reported by Swanson, 1995 [22]: the comparison, for a profile perpendicular to the line, gave agreement with a maximum error of ±7% ± 1 nT between measurement and calculation. While this comparison was for a 30 min period with constant currents, in our study, we also compare the temporal averages for longer periods with varying currents, and in addition have to evaluate the influence of simplifications, such as the constant value for the line sag and the use of symmetric currents. The explicit consideration of the effect of diurnal and seasonal variation in load flow is also a main difference from previous studies [20,23], where annual averages of currents have mostly been used for magnetic field calculations.

The precision of our results is of the same order as in [22]. For points near the line axis, it depends sensitively on the precision of the numerical terrain model. Given reliable height information and a reliable terrain model, the average relative precision (for a collection of points) is in the order of less than five per cent and standard deviation between measurements and modelling was less than ten per cent. The largest errors result from uncertainties in the coordinates, i.e., the x-y-coordinates, the height (both of conductors and terrain), and the line sag. The fact that the difference between the coarse and the fine terrain model is most pronounced for near points is to be expected, as the distance to the conductors is most strongly influenced by the height, and errors in the height act proportionally (or even stronger) on the calculated fields. For far points, the accuracy of the horizontal distance is more crucial, which is little dependent on the terrain model. The largest deviances between model and measurement were between −28% and +29%. One of these large deviations was caused by an artefact, which was due to an iron cover of a manhole close to the measurement device. This demonstrates that the magnetic fields are not only influenced by their primary sources (the high voltage line) alone, but may also be affected by conducting and/or magnetisable objects near the measurement points, where induced currents may occur in these objects and produce secondary magnetic fields. The reason for the other two large deviances remains unclear. A possible explanation may be due to the neglect of currents induced in the ground and shield wires and non-symmetric currents. Such currents are typically small (a few per cent of the symmetric currents), but as they produce fields that fall off less rapidly with distance than the fields from the symmetric currents, the fields from these unbalanced currents become relatively more important at large distances, where these large deviances were observed. Swanson [22] has included these unbalanced currents in the calculation. His Figure 11 shows that (for the line studied) the influence of the unbalanced currents remains negligible out to distances of approximately 100 m, where the magnetic field is reduced to about 98 nT or 4% of the value at line centre. Beyond that, their influence starts to grow, and at 200 m, they account for about one third of the calculated value of approx. 20 nT. A possibility to reduce the errors at large distances could therefore be to include the contributions from these induced currents. This could be done in principle, as the induced currents can be calculated from the symmetric currents and the electric and geometric properties of the conductors by applying the laws of induction. However, yet more information on the power line would have to be obtained and entered into the model, and it would only significantly affect the model in regions where the fields from the power line have already dropped to levels smaller than, e.g., the ambient levels found in typical households (ca. 50 nT, [21,24,25]), given that the observed discrepancies correspond to absolute errors of a mere 18 nT and 14 nT, respectively.

A strength of our study is the use of accurate data for line geometry and phase arrangement as well as load flow data with high temporal resolution. If such accurate data is not available, one is forced to make rough assumptions which would severely lower the model's precision.

In order to verify that the conditions during our measurements were representative for the entire year, we have compared histograms of the meteorological data (temperature, wind, and global irradiation) from nearby stations of Meteo-Schweiz for our measurement periods to those for the entire year and concluded that they agreed well. Further, the temperature measurements made with the temperature loggers inside the boxes showed that the measurement devices always stayed in the specified range, even during cold winter nights when the outside temperature was below zero, due to the thermal insulation and buffering with PCM.

5. Conclusions

Repeated measurements with twelve measurement periods of 48 h distributed over a year at two measurement sites below two different power lines demonstrate the validity of our model to estimate time-averaged magnetic fields from power lines, taking into account both diurnal and seasonal variations of load flow and changing load flow directions. The accuracy of the model depends on the availability of accurate load and geometric data. In particular, the precision for near points depends strongly on the height information and can be improved by using an accurate digital terrain model. The application of the model on a national scale seems feasible; however, a considerable work effort would be required, as e.g., for Switzerland, the geometric data of some hundred overhead lines of $\geq$220 kV would have to be entered into the model.

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Author Contributions: Alfred Bürgi developed the model, managed the project, evaluated the data, and wrote the paper draft, Sanjay Sagar performed the measurements, searched for sites, managed the data, and revised the paper draft, Benjamin Struchen helped with the EMDEX devices and the site selection, Martin Röösli was thesis advisor of the two Ph.D. students Sanjay Sagar and Benjamin Struchen, and revised the paper draft. Stefan Joss was project responsible at FOEN.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Technical data of the magnetic field measurement devices.

	Emdex II	*ESTEC DL-MW 10s*	*ESTEC EMLog 2e*
Manufacturer	EMDEX-LLC (www.emdex-llc.com)	ESTEC (www.estec.de)	
Measurement range	300 µT	130 µT	10 µT
Resolution	10 nT	10 nT	1 nT
Precision	±3% (overall) ±10% (worst case)	±3%, ±10 nT (one axis)	±3%, ±1 nT (one axis)
Axis-directions	*Y*-axis parallel to long side of devices	*X*-axis parallel to long side of devices	
Frequency bands	Broadband: 40–800 Hz Harmonics: 100–800 Hz	5–30 Hz 37–2000 Hz	
Data rate	1.5–327 s	1 s	
Battery-capacity [1]	ca. 90 h	7 days	
Number of data points, Recording-period [1]	15,000 <62 h	5,500,000 7 days	
Power source	9V Alkaline battery	Li-Ion, chargeable via USB-cable	
Data storage	Data deleted on power-off	Permanent storage	
Operating temperature range	0–60 °C	0–40 °C	

Data according to the data sheets of the manufacturers [1] in the operating mode used during the measurements.

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Supplementary Material

Exposure Modelling of Extremely Low-Frequency Magnetic Fields from Overhead Power Lines and its Validation by Measurements

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This supplementary material contains all tables with the comparison of model and measurements

Content of the tables:

- Measurement number (M1, M2, etc.)
- Measurement device (Emdex 1, Emdex 2, …)
- D: Orthogonal distance from line axis (in m)
- $\overline{\boldsymbol{B}}$: Average absolute value of magnetic flux density (in μT), measured and modelled
- $\boldsymbol{B_{RMS}}$: Root-mean-square value of magnetic flux density (in μT), measured and modeled
- $\Delta := \frac{B\text{ (model)}-B\text{(measured)}}{B\text{(measured)}}$: Relative error of model, B is the appropriate average ($\overline{\boldsymbol{B}}$ or $\boldsymbol{B_{RMS}}$), depending on the model

The four model variants are:

- Model A: Gives the arithmetic average $\overline{\mathrm{B}}$ using the the 25-m-resolution terrain model DHM25
- Model B: Gives the RMS-mean $\mathrm{B_{RMS}}$ using the the 25-m-resolution terrain model DHM25
- Model C: Gives the arithmetic average $\overline{\mathrm{B}}$ using the the 5-m-resolution terrain model DHM5
- Model D: Gives the RMS-mean $\mathrm{B_{RMS}}$ using the the 5-m-resolution terrain model DHM5

Measurements in Iffwil

Table S1: Comparison of measurement and model for measurement M1 in Iffwil (Units: D in m, B in μT).

Measure-ment M1		***Measurement***		***Model A***		***Model B***		***Model C***		***Model D***	
Jan 2015	*D*	$\bar{B}$	B_{RMS}	$\bar{B}$	Δ	B_{RMS}	Δ	$\bar{B}$	Δ	B_{RMS}	Δ
Emdex 1	0	1.220	1.338	1.030	-16%	1.140	-15%	1.187	-3%	1.325	-1%
Emdex 2	10	0.795	0.849	0.664	-16%	0.719	-15%	0.735	-7%	0.801	-6%
Emdex 3	20	0.406	0.427	0.349	-14%	0.372	-13%	0.366	-10%	0.391	-8%
Emdex 4	40	0.166	0.175	0.120	-28%	0.129	-26%	0.121	-27%	0.130	-26%
Estec 5	80	0.034	0.036	0.034	0%	0.037	2%	0.034	-1%	0.037	2%
Emdex 6	-10	1.129	1.218	1.020	-10%	1.113	-9%	1.169	4%	1.282	5%
Emdex 7	-20	0.650	0.686	0.622	-4%	0.664	-3%	0.674	4%	0.720	5%
Emdex 8	-40	0.204	0.209	0.203	0%	0.211	1%	0.207	1%	0.215	3%
Estec 9	-80	0.049	0.049	0.049	0%	0.051	3%	0.049	0%	0.051	3%

Table S2: Comparison of measurement and model for measurement M3 in Iffwil (Units: D in m, B in μT).

Measure-ment M3		***Measurement***		***Model A***		***Model B***		***Model C***		***Model D***	
Mar 2015	*D*	$\bar{B}$	B_{RMS}	$\bar{B}$	Δ	B_{RMS}	Δ	$\bar{B}$	Δ	B_{RMS}	Δ
Emdex 1	0	1.303	1.348	1.148	-12%	1.181	-12%	1.326	2%	1.367	1%
Emdex 2	10	0.802	0.830	0.716	-11%	0.737	-11%	0.791	-1%	0.814	-2%
Emdex 3	20	0.398	0.421	0.364	-8%	0.382	-9%	0.381	-4%	0.401	-5%
Emdex 4	35	0.186	0.203	0.158	-15%	0.171	-16%	0.159	-14%	0.172	-15%
Estec 5	80	0.034	0.036	0.037	10%	0.041	11%	0.037	10%	0.041	11%
Emdex 6	-10	1.294	1.342	1.126	-13%	1.160	-14%	1.294	0%	1.334	-1%
Emdex 7	-20	0.732	0.760	0.667	-9%	0.688	-9%	0.718	-2%	0.741	-3%
Emdex 8	-40	0.221	0.230	0.221	0%	0.229	0%	0.225	2%	0.233	1%
Estec 9	-80	0.050	0.053	0.054	7%	0.056	7%	0.054	7%	0.057	8%

Table S3: Comparison of measurement and model for measurement M5 in Iffwil (Units: D in m, B in µT).

Measure-ment M5		***Measurement***		***Model A***		***Model B***		***Model C***		***Model D***	
May 2015	*D*	$\bar{B}$	B_{RMS}	$\bar{B}$	Δ	B_{RMS}	Δ	$\bar{B}$	Δ	B_{RMS}	Δ
Emdex 1	0	1.254	1.364	1.122	-11%	1.206	-12%	1.283	2%	1.389	2%
Emdex 2	10	1.018	1.100	0.912	-10%	0.982	-11%	1.024	1%	1.107	1%
Emdex 3	20	0.564	0.609	0.523	-7%	0.564	-7%	0.556	-1%	0.600	-1%
Emdex 4	35	0.261	0.280	0.234	-10%	0.252	-10%	0.236	-10%	0.255	-9%
Estec 5	80	0.044	0.046	0.049	12%	0.053	15%	0.049	13%	0.053	14%
Emdex 6	-10	1.000	1.084	0.916	-8%	0.972	-10%	1.032	3%	1.099	1%
Emdex 7	-20	0.529	0.579	0.521	-2%	0.555	-4%	0.555	5%	0.591	2%
Emdex 8	-40	0.165	0.185	0.176	6%	0.190	3%	0.178	8%	0.193	4%
Estec 9	-80	0.041	0.046	0.047	14%	0.051	11%	0.047	14%	0.051	11%

Table S4: Comparison of measurement and model for measurement M7 in Iffwil (Units: D in m, B in µT).

Measure-ment M7		***Measurement***		***Model A***		***Model B***		***Model C***		***Model D***	
Jul 2015	*D*	$\bar{B}$	B_{RMS}	$\bar{B}$	Δ	B_{RMS}	Δ	$\bar{B}$	Δ	B_{RMS}	Δ
Emdex 1	0	0.694	0.785	0.580	-16%	0.644	-18%	0.682	-2%	0.758	-3%
Emdex 2	10	0.554	0.616	0.452	-18%	0.504	-18%	0.515	-7%	0.574	-7%
Emdex 3	20	0.283	0.315	0.250	-12%	0.281	-11%	0.267	-6%	0.300	-5%
Emdex 4	35	0.124	0.137	0.111	-11%	0.125	-9%	0.112	-9%	0.127	-8%
Estec 5	80	0.022	0.024	0.023	3%	0.026	10%	0.023	4%	0.026	10%
Emdex 6	-10	0.475	0.538	0.431	-9%	0.482	-10%	0.491	3%	0.551	2%
Emdex 7	-20	0.231	0.263	0.227	-2%	0.258	-2%	0.243	5%	0.276	5%
Emdex 8	-40	0.071	0.083	0.075	6%	0.088	6%	0.077	9%	0.090	8%
Estec 9	-80	0.022	0.026	0.020	-11%	0.024	-7%	0.021	-9%	0.024	-6%

Table S5: Comparison of measurement and model for measurement M9 in Iffwil (Units: D in m, B in µT).

Measure-ment M9		***Measurement***		***Model A***		***Model B***		***Model C***		***Model D***	
Sep 2015	D	$\bar{B}$	B_{RMS}	$\bar{B}$	Δ	B_{RMS}	Δ	$\bar{B}$	Δ	B_{RMS}	Δ
Emdex 1	0	1.663	1.711	1.518	-9%	1.552	-9%	1.708	3%	1.749	2%
Emdex 2	10	1.255	1.311	1.179	-6%	1.216	-7%	1.300	4%	1.345	3%
Emdex 3	20	0.740	0.774	0.726	-2%	0.747	-3%	0.766	4%	0.789	2%
Emdex 4	35	0.380	0.394	0.358	-6%	0.365	-7%	0.362	-5%	0.369	-6%
Estec 5	80	0.067	0.069	0.085	27%	0.086	25%	0.085	27%	0.086	25%
Emdex 6	-10	1.584	1.683	1.433	-10%	1.495	-11%	1.616	2%	1.691	0%
Emdex 7	-20	0.938	1.006	0.900	-4%	0.948	-6%	0.961	2%	1.014	1%
Emdex 8	-40	0.298	0.319	0.334	12%	0.350	10%	0.340	14%	0.356	12%
Estec 9	-80	0.077	0.082	0.092	19%	0.095	16%	0.092	19%	0.095	17%

Table S6: Comparison of measurement and model for measurement M11 in Iffwil (Units: D in m, B in µT).

Measure-ment M11		***Measurement***		***Model A***		***Model B***		***Model C***		***Model D***	
Oct 2015	D	$\bar{B}$	B_{RMS}	$\bar{B}$	Δ	B_{RMS}	Δ	$\bar{B}$	Δ	B_{RMS}	Δ
Emdex 1	0	1.334	1.439	1.174	-12%	1.263	-12%	1.377	3%	1.482	3%
Emdex 2	10	1.149	1.287	0.995	-13%	1.110	-14%	1.134	-1%	1.267	-2%
Emdex 3	20	0.629	0.712	0.565	-10%	0.639	-10%	0.604	-4%	0.685	-4%
Emdex 4	35	0.283	0.320	0.250	-12%	0.286	-11%	0.253	-11%	0.290	-10%
Estec 5	80	0.045	0.051	0.051	12%	0.059	15%	0.051	12%	0.058	15%
Emdex 6	-10	0.783	0.813	0.763	-3%	0.792	-3%	0.857	9%	0.887	9%
Emdex 7	-20	0.358	0.377	0.373	4%	0.387	3%	0.392	9%	0.407	8%
Emdex 8	-40	0.116	0.123	0.133	15%	0.141	14%	0.135	16%	0.142	16%
Estec 9	-80	0.035	0.039	0.040	11%	0.043	11%	0.040	12%	0.043	11%

Measurements in Wiler

Table S7: Comparison of measurement and model for measurement M2 in Wiler (Units: D in m, B in µT).

Measure-ment M2		***Measurement***		***Model A***		***Model B***		***Model C***		***Model D***	
Feb 2015	D	$\overline{B}$	B_{RMS}	$\overline{B}$	Δ	B_{RMS}	Δ	$\overline{B}$	Δ	B_{RMS}	Δ
Emdex 1	0	0.687	0.719	0.812	18%	0.851	18%	0.705	3%	0.741	3%
Emdex 2	10	0.688	0.747	0.776	13%	0.851	14%	0.691	0%	0.758	1%
Emdex 3	20	0.538	0.600	0.569	6%	0.650	8%	0.526	-2%	0.601	0%
Emdex 4	40	0.266	0.302	0.251	-6%	0.300	-1%	0.244	-8%	0.291	-4%
Estec 5	80	0.082	0.092	0.075	-9%	0.089	-3%	0.074	-10%	0.089	-4%
Emdex 6	-10	0.577	0.588	0.671	16%	0.686	17%	0.587	2%	0.603	2%
Emdex 7	-20	0.421	0.427	0.467	11%	0.479	12%	0.421	0%	0.432	1%
Emdex 8	-40	---	---	0.208		0.216		0.199		0.207	
Estec 9	-80	0.064	0.065	0.066	3%	0.070	7%	0.065	2%	0.069	6%

Table S8: Comparison of measurement and model for measurement M4 in Wiler (Units: D in m, B in µT).

Measure-ment M4		***Measurement***		***Model A***		***Model B***		***Model C***		***Model D***	
Apr 2015	D	$\overline{B}$	B_{RMS}	$\overline{B}$	Δ	B_{RMS}	Δ	$\overline{B}$	Δ	B_{RMS}	Δ
Emdex 1	0	0.955	0.984	1.084	14%	1.112	13%	0.970	2%	0.994	1%
Emdex 2	10	---	---	1.113		1.155		1.005		1.040	
Emdex 3	20	0.845	0.883	0.892	6%	0.925	5%	0.830	-2%	0.859	-3%
Emdex 4	40	0.434	0.456	0.439	1%	0.452	-1%	0.427	-2%	0.439	-4%
Estec 5	80	0.139	0.144	0.138	-1%	0.141	-2%	0.137	-1%	0.140	-3%
Emdex 6	-10	0.814	0.835	0.927	14%	0.945	13%	0.833	2%	0.847	1%
Emdex 7	-20	0.632	0.653	0.710	12%	0.725	11%	0.647	2%	0.659	1%
Emdex 8	-40	0.314	0.325	0.354	13%	0.361	11%	0.339	8%	0.346	7%
Estec 9	-80	0.104	0.108	0.119	14%	0.121	12%	0.118	13%	0.120	11%

Table S9: Comparison of measurement and model for measurement M6 in Wiler (Units: D in m, B in μT).

Measure-ment M6		***Measurement***		***Model A***		***Model B***		***Model C***		***Model D***	
Jun 2015	*D*	$\overline{B}$	B_{RMS}	$\overline{B}$	Δ	B_{RMS}	Δ	$\overline{B}$	Δ	B_{RMS}	Δ
Emdex 1	0	1.328	1.432	1.450	9%	1.562	9%	1.228	-8%	1.320	-8%
Emdex 2	10	1.085	1.225	1.121	3%	1.267	3%	0.993	-8%	1.116	-9%
Emdex 3	20	0.701	0.821	0.689	-2%	0.809	-1%	0.639	-9%	0.746	-9%
Emdex 4	40	0.280	0.335	0.268	-4%	0.315	-6%	0.260	-7%	0.306	-9%
Estec 5	80	0.077	0.089	0.081	5%	0.089	1%	0.080	3%	0.089	0%
Emdex 6	-10	1.219	1.272	1.367	12%	1.424	12%	1.154	-5%	1.202	-6%
Emdex 7	-20	0.885	0.905	0.980	11%	1.004	11%	0.854	-4%	0.874	-3%
Emdex 8	-40	0.373	0.378	0.411	10%	0.417	10%	0.386	4%	0.392	4%
Estec 9	-80	0.094	0.097	0.112	19%	0.115	18%	0.111	17%	0.113	16%

Table S10: Comparison of measurement and model for measurement M8 in Wiler (Units: D in m, B in μT).

Measure-ment M8		***Measurement***		***Model A***		***Model B***		***Model C***		***Model D***	
Jul 2015	*D*	$\overline{B}$	B_{RMS}	$\overline{B}$	Δ	B_{RMS}	Δ	$\overline{B}$	Δ	B_{RMS}	Δ
Emdex 1	0	0.870	0.967	0.962	11%	1.076	11%	0.812	-7%	0.906	-6%
Emdex 2	10	0.774	0.883	0.786	2%	0.914	3%	0.693	-10%	0.801	-9%
Emdex 3	20	0.527	0.619	0.502	-5%	0.601	-3%	0.463	-12%	0.552	-11%
Emdex 4	40	0.219	0.260	0.198	-9%	0.236	-9%	0.192	-12%	0.228	-12%
Estec 5	80	0.061	0.069	0.057	-6%	0.063	-9%	0.056	-8%	0.063	-9%
Emdex 6	-10	0.736	0.795	0.856	16%	0.932	17%	0.723	-2%	0.786	-1%
Emdex 7	-20	0.515	0.548	0.585	14%	0.628	15%	0.510	-1%	0.548	0%
Emdex 8	-40	0.194	0.206	0.231	19%	0.247	20%	0.217	12%	0.233	13%
Estec 9	-80	0.047	0.052	0.061	29%	0.066	27%	0.060	28%	0.065	25%

Table S11: Comparison of measurement and model for measurement M10 in Wiler (Units: D in m, B in µT).

Measure-ment M10		***Measurement***		***Model A***		***Model B***		***Model C***		***Model D***	
Sep 2015	D	$\bar{B}$	B_{RMS}	$\bar{B}$	Δ	B_{RMS}	Δ	$\bar{B}$	Δ	B_{RMS}	Δ
Emdex 1	0	0.767	0.783	0.839	9%	0.862	10%	0.707	-8%	0.727	-7%
Emdex 2	10	0.708	0.719	0.735	4%	0.751	4%	0.644	-9%	0.659	-8%
Emdex 3	20	0.492	0.501	0.493	0%	0.504	1%	0.452	-8%	0.462	-8%
Emdex 4	40	0.195	0.200	0.194	0%	0.199	0%	0.187	-4%	0.193	-4%
Estec 5	80	0.049	0.051	0.050	3%	0.052	2%	0.050	2%	0.052	1%
Emdex 6	-10	0.638	0.658	0.702	10%	0.732	11%	0.594	-7%	0.619	-6%
Emdex 7	-20	0.433	0.451	0.459	6%	0.486	8%	0.402	-7%	0.424	-6%
Emdex 8	-40	0.167	0.175	0.175	5%	0.186	6%	0.165	-1%	0.175	0%
Estec 9	-80	0.041	0.043	0.046	11%	0.048	11%	0.045	9%	0.048	10%

Table S12: Comparison of measurement and model for measurement M12 in Wiler (Units: D in m, B in µT).

Measure-ment M12		***Measurement***		***Model A***		***Model B***		***Model C***		***Model D***	
Dec 2015	D	$\bar{B}$	B_{RMS}	$\bar{B}$	Δ	B_{RMS}	Δ	$\bar{B}$	Δ	B_{RMS}	Δ
Emdex 1	0	0.977	1.082	1.158	18%	1.273	18%	1.006	3%	1.105	2%
Emdex 2	10	1.021	1.162	1.158	13%	1.306	12%	1.029	1%	1.158	0%
Emdex 3	20	0.822	0.949	0.874	6%	0.999	5%	0.806	-2%	0.920	-3%
Emdex 4	40	0.385	0.450	0.392	2%	0.454	1%	0.380	-1%	0.440	-2%
Estec 5	80	0.114	0.133	0.113	-1%	0.131	-1%	0.112	-2%	0.130	-2%
Emdex 6	-10	---	---	0.906		0.966		0.796		0.851	
Emdex 7	-20	0.536	0.568	0.602	12%	0.634	12%	0.546	2%	0.575	1%
Emdex 8	-40	0.235	0.247	0.257	10%	0.270	9%	0.247	5%	0.260	5%
Estec 9	-80	0.075	0.080	0.082	9%	0.087	9%	0.081	8%	0.086	8%

5. Summary of the Main Findings

The purpose of this dissertation was to monitoring of electromagnetic field exposure in an international context. This was accomplished by four independent projects; 5.1) Systematic review of radiofrequency electromagnetic field and its exposure situation in everyday microenvironments in Europe, 5.2) Monitoring of radiofrequency electromagnetic field exposure in different everyday environments in Switzerland, 5.3) Comparison of Radiofrequency Electromagnetic Field Exposure levels in different Everyday Microenvironments in an International context, and 5.4) A Method to calculate annual averages and its validation by measurements of magnetic fields from high voltage overhead powerlines.

5.1. Systematic review

The main aim of the RF-EMF review project was to systematically review the RF-EMF exposure situation in the European countries based on peer-reviewed articles on spot measurements studies, personal measurement studies with trained researchers, and personal measurement studies with volunteers. The systematic review of 21 eligible articles published between 01st January, 2000 and 30th April, 2015 assessed RF-EMF exposure levels by three methods; spot measurements, personal measurement studies with trained researchers (microenvironmental), and personal measurement studies with volunteers. Out of 21 eligible studies assessed, we found 10 were spot measurements, 5 were personal measurement studies with trained researchers, 5 were personal measurement studies with volunteers and 1 was mixed study combining data collected by volunteers and trained researchers. This literature review of the RF-EMF exposure assessment was conducted across 29 European countries; 11 out of the 29 European countries have conducted at least one RF-EMF exposure assessment since 2000.

All of the 21 eligible studies have used some kind of sampling strategies; spot measurement studies have used random sampling, representative but not random or selective criteria for microenvironment selection, personal measurement studies with trained researchers have used representative but not random selection criteria for microenvironment selection. Personal measurement studies with volunteer studies have used either random or unselected sampling techniques for volunteer selection. The use of RF-EMF measuring devices varied across the types of study; Spectrum analyzer and different version of EME Spy were used for spot measurement, EME Spy 120 and a three-axis measuring antenna were used for personal measurements with trained researchers, and different version of EME Spy (EME Spy 140, 121 and 120) were used for personal measurements with volunteer studies.

The RF-EMF exposure levels were analyzed by “Home”, “Outdoor microenvironments” and “Public transport”. Mean exposure levels at “Homes” ranged between 0.12 V/m and 0.37 V/m in the personal measurements with trained researchers and personal measurements with volunteer studies respectively. The average value over all spot measurement studies at “Homes” was 0.29 V/m. Downlink and DECT contributed the most to the total RF-EMF in “Homes”. Mean exposure at “Outdoor” microenvironments ranged between 0.11 V/m and 1.59 V/m, and 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 to spot measurement studies (0.54 V/m) and personal volunteer studies (0.32 V/m). Downlink contributed the most to the total RF-EMF in “Outdoor” microenvironments in all measurement studies with trained researchers and all spot measurement studies except urban outdoor environment of Reading, UK. Mean RF-EMF exposure in public transport ranged between 0.004 V/m in car/van/truck (Switzerland) to 1.96 V/m in train (Belgium). 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 to 0.43 V/m across personal measurement studies with volunteers.

5.2. NIR Monitoring in Switzerland

The main aim of the non-ionizing (NIR) monitoring in Switzerland was to test the suitability of microenvironmental measurement surveys with portable exposimeters (PEM) for monitoring of RF-EMF levels in various everyday microenvironments in Switzerland. The non-ionizing radiation (NIR) monitoring was conducted in 51 different microenvironments in Switzerland between 25th March and 11 July 2014 by two different trained study assistants carrying a backpack, with portable ExpoM-RF on the top, approximately 20-30 cm away from body so as to minimize the body shielding and to ensure the mobility. This portable ExpoM-RF device is capable of quantifying RF-EMF exposure within 16 different frequency bands ranging from 87.5 to 5875 MHz. Each of the selected microenvironments was comprised of two different paths i.e. path 1 and path 2 (possibly non-overlapping but preferably intersecting). Each path measures a length of about 1 km to be covered by walking in approximately 15 minutes. A measurement was taken every four second. The person taking the measurements was instructed to use the right hand side of the road whenever suitable. The study assistants were further instructed to turn off the personal mobile phone during the measurements. A mobile phone with a TimeStamp App was used in flight mode to record the start and end times of each walk along a predefined path. Most of the measurements were taken during weekdays except the first measurement in Aarau, Lausanne and Pully (Aarau on Saturday, Lausanne and Pully on Sunday). To track the assigned path when walking, the inbuilt GPS of the ExpoM-RF was used.

The 16 different frequency bands ranging from 87.5 to 5875 MHz of the ExpoM-RF device was categorized into five relevant frequency groups: i) Uplink (mobile phone handset exposure): sum of mean power densities of all uplink frequencies (LTE800 Uplink), (Uplink900), (Uplink1800), (Uplink1900), and (LTE2600 Uplink); ii) Downlink (mobile phone base station exposure): sum of mean power densities of all downlink frequencies (LTE800 Downlink), (Downlink900), (Downlink1800), (Downlink2100), and (LTE2600 Downlink); iii) Broadcasting: sum of mean power densities of all the radio spectrum used for broadcasting (FM), and (DVB-T); iv) others; sum of mean power densities of frequency namely (DECT), (WLAN; ISM 2.4 GHz), and (WLAN; ISM 5.8 GHz). v) total RF-EMF exposure: sum of mean power densities of all frequency bands except (WiMax 3.5 GHz). We excluded WiMax 3.5 GHz since it is not used in Switzerland.

All analyses were done by statistical software R version 3.1.3 (https://www.r-project.org/). The analyses of the monitoring of RF-EMF exposure from 51 different microenvironments showed that mean RF-EMF exposure (sum of 15 main frequency bands between 87.5 and 5,875 MHz) was 0.53 V/m in industrial zones, 0.47 V/m in city centers, 0.32 V/m in central residential areas, 0.25 V/m non-central residential areas, 0.23 V/m in rural centers and rural residential areas, 0.69 V/m in trams, 0.46 V/m in trains and 0.39 V/m in buses. Major exposure contribution at outdoor locations was from mobile phone base stations (>80% for all outdoor areas with respect to the power density scale). Temporal correlation between first and second measurement of each path was high: 0.83 for total RF-EMF, 0.83 for all five mobile phone downlink bands combined, 0.54 for all five uplink bands combined and 0.79 for broadcasting. Spearman correlation between arithmetic mean values of the first path compared to arithmetic mean of the second path within the same microenvironment was 0.75 for total RF-EMF, 0.76 for all five mobile phone downlink bands combined, 0.55 for all five uplink bands combined and 0.85 for broadcasting (FM and DVB-T). This study showed that microenvironmental surveys using a portable device yields highly repeatable measurements, which allows monitoring time trends of RF-EMF exposure over an extended time period of several years and to compare exposure levels between different types of microenvironments.

5.3.NIR Monitoring Internationally

The aim of the international RF-EMF monitoring study was to conduct measurements in different microenvironments in Switzerland, Ethiopia, Nepal, South Africa, Australia and the United States of America with portable devices using a high sampling to monitor RF-EMF exposure levels in a representative and efficient manner. We used ExpoM-RF and EME Spy 201 to monitor the exposure; ExpoM-RF was used to monitor RF-EMF exposure in Switzerland, Ethiopia, Nepal, South Africa and Australia, and EME Spy 201 was used in the United States. We measured 94 different microenvironments using ExpoM-RF and 8 microenvironments using EME Spy 201. All the measurements were taken either by walking with a bag pack with the devices at the height of the head in a distance of 20-30 cm from the head or driving a car with devices mounted on its top. All the measurements were taken during daylight except the half of the measurements in the United States of America. The measurements were taken for about 30 minutes while walking and about 15-20 minutes while driving in each microenvironment with a sampling rate of 4 seconds for ExpoM-RF device and 5 second sampling rate for EME Spy 201. Descriptive statistics of all the measurements among six countries showed that mean total RF-EMF exposure in all 6 countries in various microenvironments varied between 0.33 V/m and 1.85 V/m, and across public transports RF-EMF exposure varied between 0.36 V/m and 0.67 V/m. The highest mean total RF-EMF exposure was 1.85 V/m in the university areas in Australia and the lowest 0.33 V/m in rural centers and rural residential areas in South Africa. For outdoor areas major exposure contribution was from mobile phone base station. The mobile phone base stations contributed more than 65% in all measured microenvironments across the 6 countries. In the public transports, the highest total mean exposure was 0.67 V/m in tempo in Lalitpur Nepal and the lowest 0.36V/m in bus in Seewen Switzerland. The highest exposure from mobile phone handsets was 0.44 V/m in trains in Zurich and lowest was 0.11 V/m taxi, tempo and police van in two major cities (Lalitpur and Bhaktapur) in Nepal. In terms of reproducibility, Pearson correlation between the first and the second measurements (arithmetic mean values) was highly correlated. For example, Pearson correlation between the two measurements in Switzerland was 0.97 for total and downlink, 0.96 for uplink and 0.99 for broadcasting.

5.4.Powerline study

The main aim of the powerline study was to present a validated a 3D computer model for calculating long term exposure to extremely low frequency magnetic fields from high-voltage overhead power lines. This project comprised of two components; the first part was a feasibility and pilot study where a 3D computer model was developed and possible data sources were evaluated. This model was then applied to a 31 km long section of a line with two 220-kV systems and exposure maps for the length of the section were calculated. The second part was a validation study where the methodology derived in the feasibility and pilot study was validated with a sample survey of measurements. These measurements were carried out at two different measurement sites under two different high-voltage overhead power lines. In order to capture the daily and seasonal variations, each measurement was taken for 48 hours and the measurements were carried out six times at each site, at intervals of approximately two months, between January and December 2015. During each measurement, a lateral profile of the magnetic flux density was determined in the middle of a span from nine measurement points in the range of ±80 m. The technical data of both lines as well as the load flow data during the measurement periods were provided by the grid operators (Swissgrid and BKW). These data were used to calculate temporal averages of the absolute value of the magnetic flux density using the model for each measurement period and each measurement point, and these values were then compared to the measured temporal averages. The comparison of calculated and measured temporal averages of the magnetic flux density showed a very good agreement, and the deviations were of the order that had been predicted in the pilot study.

The both components of the study helped in identifying the input data necessary for large-scale modeling of magnetic fields from high-voltage power lines and how long-term temporal averages of the field can be computed. We obtained the data for an actual section of a power line to calculate exposure maps and quantified the work effort needed to do so. We also estimated the precision of the results to be of the order of 10 % to 25 %, and found that the precision is to a large degree caused by errors in the coordinates and heights. We also conducted repeated measurements with twelve measurement periods of 48 hours distributed over a year at two measurement sites under two different power lines to validate the model with measured data. We found that the model agreed well with the measurements, with average offsets in the range of a few percent. We also found that the precision of the results corresponds to the precision estimated during the pilot study. The precision for near points depends strongly on the height information and can be improved by using an accurate digital terrain model.

6. Discussion

6.1.Overall Significance of Research

This research has direct practical applications and provides much needed EMF exposure situation reporting globally for better planning of epidemiological studies and recommendations for policy makers. The content of the thesis is broad, incorporating radiofrequency monitoring in six different countries across four continents and developing a 3D computer model to measure extremely low frequency magnetic fields from overhead powerlines in Switzerland. A variety of methods were employed, including systematic literature review, RF-EMF exposure assessment, ELF-MF exposure assessment, statistical analyses, modelling and exposure prediction. There was almost a complete absence of pre-existing high quality comparative information on EMF across all countries before this thesis research began.   This RF-EMF monitoring study was the first study to estimate the exposure of the population by providing RF-EMF measurements for various countries on different continents using the same type of measurement devices and measurement protocol. Most importantly, the data were collected at representative locations, where people spend most of their time either walking or driving a car. Further, the project provided novel data to evaluate spatial differences of RF-EMF exposure within and between countries from different continents. Previous monitoring activities had been restricted to Europe and were mostly limited to a few sources with a low spatial resolution (Dürrenberger G, et al 2014). Exposure sources such as wifi, broadcasting or uplink exposure were also covered in the present study, which are highly relevant for assessing total exposure of the population but which had not been included in previous monitoring activities that mostly focused on mobile phone base station exposure.

6.2.Innovation, Validation and Application

This work was realized in the context of the public health continuum of “innovation, validation and application”, which underlies research at the Swiss Tropical and Public Health Institute. By definition, innovation refers to novel ideas/concepts, methods or approaches;

validation refers to scrutinizing such innovation; and application refers to the implementation of validated ideas in everyday life. This PhD thesis contributes to all the three notions as described in the Table 5.

Table 5: Classification of research projects in terms of innovation, validation and application wings of Swiss TPH

Chapter	Title	Innovation	Validation	Application
4.1	Radiofrequency electromagnetic field and its exposure situation in everyday microenvironments in Europe: a systematic literature review	The approach of this review was novel and innovative as we applied systematic review techniques for exposure assessment which is not common techniques as it is for health reviews.		Systematic review methodology was used to describe RF-EMF summary and knowledge gap
4.2	Use of Portable Exposimeters to Monitor Radiofrequency Electromagnetic Field Exposure in the Everyday Environment	A pilot study to test a common protocol to assess RF-EMF exposure for direct comparison of the measurements in various microenvironments.		
4.3	Comparison of Radiofrequency Electromagnetic Field Exposure levels in different Everyday Microenvironments in an International context		Tested protocol validated by a larger RF-EMF monitoring	Application of tested protocol to monitor RF-EMF from 6 different countries across 5 continents
4.4	Magnetic Fields from High-Voltage Overhead Powerlines: A Method to calculate Annual Averages and its Validation by Measurements	A reliable and cost effective 3D computer model developed to measure ELF-MF from overhead powerlines	The model was validated with field measurements	

6.3.Research Outputs versus Objectives

6.3.1 Systematic Review of RF-EMF (Objective 1)

The first project of this study, the systematic review, was the first of its kind to review the RF-EMF exposure situation from different sources in everyday microenvironments, such as city centers, downtown, residential areas, home, workplaces, airports and so forth. The review also shed light on different sources of RF-EMF exposure in microenvironments, including public transportation. The review summarized RF-EMF exposure in various microenvironments across 29 European countries, as presented in Chapter 4.1. The review identified an important knowledge gap that could help mitigate public concerns about electromagnetic exposure and potential health risk as well as enable effective exposure policies, including appropriate risk communication.

6.3.2 NIR Monitoring in Switzerland (Objective 2)

The second project of this study, monitoring non-ionizing radiation in Switzerland, measured RF-EMF in different microenvironments using a common protocol, which allowed direct comparison of the measurements in various microenvironments, as presented in Chapter 4.2. For a better comparison of the RF-EMF exposure in various microenvironments, monitoring was conducted by two trained researchers and all data analyses were performed by a single researcher following the same data analyses procedures for all datasets. Personal mobile phones were turned off while trained researchers took measurements allowing only exposure from other people`s mobile phone handsets to be captured. This monitoring study also minimized body shielding issues through putting the device on the top of a backpack at a distance of about 20-30 cm from the body and slightly above the height of the head. While traveling by public transport, the backpack was either carried by the study assistant or was kept vertical on the seat of vehicle to ensure minimum shielding. Previous studies have shown that keeping the device close, within 10-50 mm of the body, underestimates the incident field strength by approximately 10 to 50% for different RF-EMF bands (Blas et al., 2007; Bolte & Eikelboom, 2012; Iskra et al., 2010; Knafl et al., 2008; Neubauer et al., 2007a; Radon et al., 2006). This project served as a pilot study for a larger international study across five continents.

6.3.3 NIR Monitoring Internationally (Objective 3)

The third project on non-ionizing radiation monitoring internationally resulted in the first standardized comparison of RF-EMF exposure across several countries, as the measurements were conducted following a common tested protocol. A unique aspect of this study was that all the measurements were conducted by walking with a backpack with the measurement device on the top, at a distance of about 20-30 cm from the body and slightly above the height of the head, or by driving a car with the device mounted on the roof to minimize shielding. All the data analyses were performed by one of person to assure homogeneity of the data analyses and reporting of the findings, as presented in Chapter 4.3.

6.3.4 Powerline Study (Objective 4)

The fourth project on the powerline study was the first of its kind to present a 3D computer model for calculating long-term exposure to extremely low frequency magnetic fields from high-voltage overhead power lines, as presented in Chapter 4.4. Epidemiological studies on potential health risks from ambient extremely low frequency- magnetic fields (ELF-MF) have been hampered by the lack of a validated exposure assessment method for ELF-MF and the high cost associated with the longer time frame required. This project resulted in a validated low-cost model for assessing ELF-MF that could be applied to any overhead powerline emissions, if the necessary input data is available. The second component of the study validated the 3D computer model that required real field measurement from overhead powerlines. This real time measurement was useful to describe ELF-MF exposure over 48 hours across six measurements throughout the year. To the best of our knowledge, this is the only study to measure the ELF-MF up to 50 meters on either side of the source of emission.

6.4.Application of Research

The direct applications of the four projects of this study are as follows:

- The systematic review of RF-EMF will narrow the knowledge gap and enable effective exposure policies, including appropriate risk communication. This is of particular interest to telecommunication industries and policy makers as well as to advocacy groups.

- Lay people and even experts have little knowledge about EMF exposure; the findings of the review and RF-EMF monitoring will provide the most up-to-date information to both lay people and experts.
- The findings relating to review and monitoring of RF-EMF exposure in different microenvironments will guide the design of future epidemiological studies.
- Exposure to RF-EMF is inevitable due to continued advancements in the telecommunication industry and to the integral role of telecommunication in daily life. One can minimize personal exposure based on the findings from non-ionizing radiation monitoring.
- Although health effects from exposure to RF-EMF have not yet been well established, it would be useful to adopt a preventive approach while waiting for the outcome of long-term exposure studies.
- The RF-EMF exposure situation is continuously changing as newer technologies are introduced; therefore, continuous RF-EMF monitoring is required at local, regional and national level.
- The 3D computer model will enable epidemiological studies on potential health risks from ambient ELF-MF that have been hampered by the lack of a validated exposure assessment method for ELF-MF and by the high cost associated with the longer time horizon required.

  ELF-MF exposure findings show how the exposure varies across different times of the day and different seasons of the year, useful information for the general public and experts alike.

6.5.General Recommendations and Future Research

Recommendations arising out of these four projects and directions for further research are discussed below:

6.5.1 Systematic Review of RF-EMF (Objective 1)

General recommendations:

- Not much has been done to secure investments in RF-EMF monitoring on an annual basis. Advocacy groups could target national and international bodies, to this end.
- Most RF-EMF studies are limited to Europe; researchers and scientists from the rest of the world should be trained to conduct high quality RF-EMF research.

- Educating communities to minimize their exposure to RF-EMF and to fill the knowledge gap could be communicated through verbal and visual health messages developed by local, regional and national advocacy groups.

Future research:

- Understanding the RF-EMF exposure situation in Asia, Africa, Australia, South America and North America could help compare the greater exposure situation and knowledge gap.

6.5.2 NIR Monitoring in Switzerland (Objective 2)

General recommendations:

- Challenges and uncertainty around RF-EMF comparison should be dealt with by developing a common protocol for RF-EMF exposure assessment at national level .
- Increase funding for EMF research to enable continuous RF-EMF monitoring that keeps pace with technological advancements.
- Educate communities to minimize the risk of exposure to RF-EMF and to reduce the knowledge gap by communicating verbal and visual health messages designed by the local, regional and national advocacy groups.

Future research:

- Night time RF-EMF monitoring could be interesting to observe the exposure situation when people are inactive on telecommunication.
- Annual RF-EMF monitoring data would enable a sophisticated epidemiological study on RF-EMF exposure and health outcomes.
- Newer RF-EMF measurement devices should be developed to cope with technological advancements.

6.5.3 NIR Monitoring Internationally (Objective 3)

General recommendations:

- Challenges and uncertainty around RF-EMF comparison should be dealt with by developing a common protocol for RF-EMF exposure assessment at international level.

- Advocacy groups should targeting national and international bodies to secure more investment in RF-EMF monitoring on an annual basis.
- Funding for RF-EMF monitoring studies should be in line with technological development to better understand the exposure situation.
- The precautionary limits to RF-EMF exposure should be amended. Although no health effects have been established below the limits to date, the uncertainties of long-term EMF exposure call for a cautionary approach.
- Exposure from broadcasting and wifi bands is on rise and we lack clear cut limit values for causing health effects. Precautionary limits for such bands are immediately required.
- Educate communities to minimize the risk of exposure to RF-EMF and to reduce the knowledge gap by communicating verbal and visual health messages developed by local, regional and national advocacy groups.

Future research:

- Monitor exposure levels during night time, when the emissions from mobile phone base stations are lower.
- Future research should also look at the biological mechanisms of RF-EMF exposure while continuing environmental RF-EMF exposure monitoring.
- Study effects of ambient low-dose exposure to RF-EMF over the long term.

6.5.4 Powerline Study (Objective 4)

Future research:

Epidemiological studies of the potential health risks from exposure to ambient ELF-MF with the validated cost effective 3D computer model.

6.6.Final Conclusions

This PhD thesis addresses two issues relating to EMF, namely the knowledge gap around RF-EMF in different microenvironments and a 3D computer model for establishing epidemiological studies of potential health risks from ambient ELF-MF exposure. To resolve these issues, four research projects were conducted across the continuum of innovation-validation-application that forms the basis of the activities at the Swiss Tropical and Public Health Institute. The results from all four projects make valuable contributions to global and local research and knowledge around EMF. Apart from direct applications, this thesis research also provides evidence-based information from which individuals, communities, and other stakeholders can take appropriate decisions and actions.

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Publications

Peer reviewed articles

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2017 — Bürgi, A., **Sagar, S**., Struchen, B., Joss, S., & Röösli, M. (2017). Exposure Modelling of Extremely Low-Frequency Magnetic Fields from Overhead Power Lines and Its Validation by Measurements. International Journal of Environmental Research and Public Health, 14(9), 949. https://doi.org/10.3390/ijerph14090949 (Joint Authorship)

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