Exposure assessment of radiofrequency electromagnetic fields (RF-EMFs) in everyday environments – methodological approaches and issue-specific perspectives

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von Damiano Urbinello
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Genehmigt von der Philosophisch-Naturwissenschaftlichen Fakultät auf Antrag von

Prof. Dr. Martin Röösli, Schweizerisches Tropen- und Public Health-Institut, Universität Basel (Dissertationsleiter)
Prof. Dr. Wout Joseph, Departement für Informationstechnologie, Universität Ghent (Co-Dissertationsleiter)
Dr. Jürg Fröhlich, Institut für Feldtheorie und Höchstfrequenztechnik, Eidgenössisch Technische Hochschule Zürich (Korreferent)
Prof. Dr. Marcel Tanner, Schweizerisches Tropen- und Public Health-Institut, Universität Basel (Fakultätsverantwortlicher)

Basel, den 10. Dezember 2013

Prof. Dr. Jörg Schibler
Dekan der Philosophisch-Naturwissenschaftlichen Fakultät der Universität Basel

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Swiss TPH
Swiss Tropical and Public Health Institute
Schweizerisches Tropen- und Public Health-Institut
Institut Tropical et de Santé Publique Suisse

Associated Institute of the University of Basel

Approved from the Faculty of Engineering and Architecture of Ghent University at the request of

Prof. Dr. Wout Joseph, Ghent University (Co-Supervisor)
Prof. Dr. Martin Röösli, Swiss Tropical and Public Health Institute, University of Basel (Supervisor)
Prof. Dr. Patric De Baets, Ghent University (Chairman)
Prof. Dr. Marcel Tanner, Swiss Tropical and Public Health Institute, University of Basel (Responsible of the faculty, co-chair)
Prof. Dr. Heidi Steendam, Ghent University (Member of the PhD committee)
Prof. Dr. Luc Martens, Ghent University (Member of the PhD committee)
Prof. Dr. Anke Huss, (Member of the PhD committee)

Ghent, 27th November 2013

Prof. Dr. Rik Van de Walle
Dean of the Faculty of Engineering and Architecture of Ghent University

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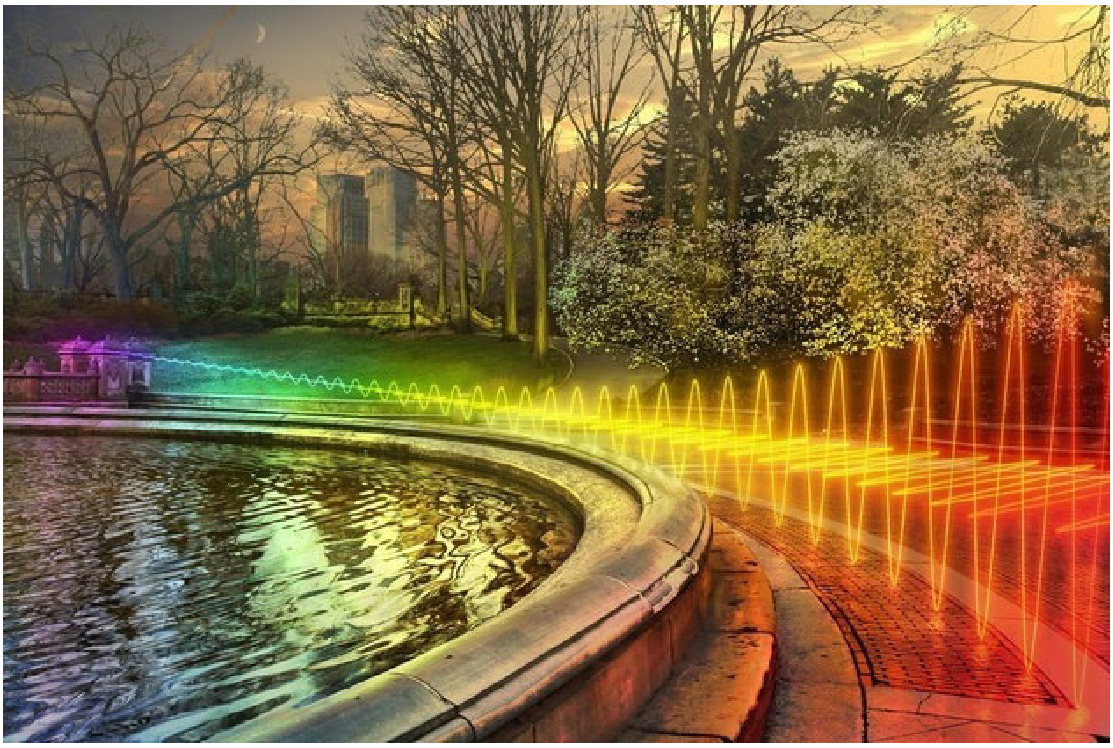

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Wenn die Wissenschaft ihren Kreis durchlaufen hat, so gelangt sie natürlicher Weise zu dem Punkte eines bescheidenen Misstrauens, und sagt, unwillig über sich selbst: Wie viele Dinge gibt es doch, die ich nicht einsehe.

Immanuel Kant

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List of Abbreviations

ANOVA	Analysis of Variance
APC	Adaptive Power Control
CI	Confidence Interval
COSMOS	Cohort study of mobile phone use and health
dB	Decibel
DECT	Digital Enhanced Cordless Telecommunication
DNA	Desoxyribonucleic acid
EMF	Electromagnetic field
EEG	Electroencephalography
ETH	Eidgenössisch Technische Hochschule Zürich Swiss Federal Institute of Technology Zurich
FM	Frequency Modulation
GSM	Global System for Mobile Communications (2nd generation)
Hz	Hertz: unit for frequency
HSPA	High Speed Packet Access
IARC	International Agency for Research on Cancer
LOS	Line-of-sight
LF	Low-frequency
LF-EMF	Low-frequency electromagnetic field
LTE	Long-term Evolution (4th generation)
m	Meter
Mbit	Megabyte
MHz	Mega Hertz

NLOS	Non-line-of-sight
OR	Odds ratio
RF	Radio-frequency
RF-EMF	Radio-frequency electromagnetic field
ROS	Regression on order statistics
s	Second
SAR	Specific energy absorption rate [W/kg]
Swiss TPH	Swiss Tropical and Public Health Institute
TV	Television
UMTS	Universal Mobile Telecommunications System (3^{rd} generation)
WHO	World Health Organization
WiMax	Wireless Interoperability for Microwave Access
WLAN	Wireless Local Area Network

Definitions

Downlink	Communication from mobile phone base stations to mobile phone handsets.
Handover	The mobile phone informs the cellular network about changes in its location area during an active call.
Location area update	The mobile phone in stand-by mode informs the cellular network about changes in its location area.
Odds Ratio (OR)	Measure of association between an exposure and an outcome.
Uplink	Communication from mobile phone handsets to mobile phone base stations.
TETRAPOL	Professional radio communication standard for emergency units.

Summary

Introduction and objectives

There was a substantial development and persistent introduction of new telecommunication devices in the past two decades. Mobile communication is nowadays ubiquitous reaching a number of mobile-cellular subscriptions of around 6.8 billion in 2013 – almost as many as the entire population worldwide. This widespread use of mobile telecommunication required an expansion of the network to meet the new technological requirements and end-user demands. In the meantime, a shift could be observed from text messaging and calls towards mobile internet access through mobile devices which will continue to grow strongly. All these developments led to a substantial change of the radiofrequency electromagnetic field (RF-EMF) exposure situation and to concerns about potential adverse health effects in the population. Countries thus started to introduce precautionary exposure limits in order to decrease the exposure of the population. However, there is no study so far scrutinizing what consequences such precautionary limits have on outdoor exposure levels. The Research Agenda of the World Health Organization (WHO) classified EMF research as a high research priority. Measurement devices allowing to quantify personal RF-EMF exposure became available only some years ago. Accordingly, several studies have been conducted using personal measurement devices (exposimeters). However, such measurements had typically been conducted through recruited study participants being allowed to use their own mobile phone during measurements. This can limit data interpretation if one is interested to differentiate between the exposure from the own mobile phone and from the exposure of other people's mobile phone. Still, little is known about the exposure situation in our everyday life and how RF-EMF exposure changed over time. Exposure assessment has become challenging, due to the high spatial and temporal variability of RF-EMFs, questioning how reproducible personal exposure measurements are.

Objectives

In the framework of this dissertation, methodological and issue-specific questions have been examined. From a methodological point of view, we aimed to investigate the effect of the own mobile phone on personal measurements. As our

measurements based on a repetitive data collection procedure at defined time frames and with predetermined measurement sequences, we studied the reproducibility of personal RF-EMF measurements over time using an exposimeter. Furthermore, we aimed to inspect how the mobile station network affects exposure situations in outdoor areas.
Issue-specific research questions focussed on the characterization of RF-EMF exposure levels in typical everyday environments and how exposure changed over time.

Methods
Measurements were conducted during different time periods between 3 weeks and 1 year in several environments and across several European cities, i.e. Basel (Switzerland), Amsterdam (the Netherlands), Ghent and Brussels (Belgium). We used an exposimeter of the type EME Spy 120 for quantifying RF-EMF exposure on different frequency bands ranging from FM (Frequency Modulation, 88 MHz) to WLAN (Wireless Local Area Network, 2.5 GHz), including all telecommunication signals: GSM 900 (Global System for Mobile Communications), GSM 1800 and UMTS (Universal Mobile Telecommunications System) in up- (UL, communication from mobile phone to base station) and downlink (DL, communication from base station to mobile phone) traffic. We included different typical everyday environments in outdoor areas, public transports, and indoor settings.

Results
Primarily, results on methodological questions showed that the own mobile phone in stand-by mode reached exposure levels up to a factor of 100 compared to a mobile phone being turned off. These results were more pronounced during car rides whether during rides in public transports, as the background exposure, especially in trains, was relatively high. Analysis of variance (ANOVA) indicated that despite the high spatial variability which was best explained by the type of area (30%) in urban cities and the type of city (50%), mobile phone base station exposure in outdoor urban areas was highly reproducible. Typical mobile phone base station exposure levels in outdoor urban areas (all types of outdoor urban areas combined) across different European cities ranged between 0.22 V/m in Basel and 0.43 V/m in Amsterdam. Peak exposure levels reached values of up to 0.82 V/m (Amsterdam) for

the 95th percentile and the highest percentage of exposure (99th percentile) showed values which were between 0.81 V/m (Basel) and 1.20 V/m (Brussels).
Analyses relating to issue-specific questions showed consistently during all measurements that highest total average RF-EMF levels occurred in trains with exposure levels between 0.83 V/m (Ghent) and 1.06 V/m (Brussels) and in downtown areas: 0.32 V/m (Ghent) to 0.58 V/m (Brussels). The total RF-EMF exposure increased by 20% in Ghent, by 38% in Brussels and by 57% in Basel during the study period of one year between April 2011 and March 2012 in all outdoor areas in combination.

Discussion and Outlook

Characterizing RF-EMF exposure with personal exposimeters has shown to be feasible for quantifying exposure levels and to investigate temporal trends. They allow collecting large amounts of data with little effort and enable including a large variety of different environments. In addition, our study demonstrated that measurements were highly reproducible for mobile phone base station exposure in outdoor urban areas which is a strength when planning exposure assessment studies based on repeated measurements. However, when taking measurements it is recommended to turn off the own mobile phone, as our results showed a considerable impact of the own mobile phone on personal measurements. The contribution to total RF-EMF exposure was predominantly influenced by telecommunication technologies, i.e. mobile phones and mobile phone base stations, representing the most important sources of exposure in outdoor areas, public transports and indoor settings. All exposure levels were far below the frequency-dependent reference levels (41–61 V/m) proposed by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) as well as below national imposed precautionary limits implemented in the different countries (on average ten times lower than ICNIRP levels). Furthermore, our study did not find any indications that lowering the regulatory limits result in higher mobile phone base station exposure levels so far; nevertheless, further studies including more cities with different regulatory limits are needed. A monitoring of the exposure to RF-EMFs is important nowadays, especially with the introduction and expansion of new technologies and the increased usage of mobile telecommunication. Monitoring studies should help to clarify how RF-EMF exposure levels change over time and allow identifying areas

with critical exposure values. These studies may contribute to a better understanding of potential adverse health effects. Global research efforts are highly needed to translate findings in public policies. In the light of current uncertainties regarding potential adverse health effects due to long-term low-dose exposure levels, minimizing exposure might be reasonable and requested.

Zusammenfassung

Einführung

Seit zwei Jahrzehnten ist ein bedeutsamer Anstieg bei der Entwicklung und Einführung neuer mobiler Telekommunikationsmittel zu verzeichnen. Die Mobiltelefonie ist heutzutage allgegenwärtig, was sich auch an der Anzahl abgeschlossener Mobiltelefon-Verträge weltweit zeigt, die mit 6.8 Milliarden beinahe ebenso hoch liegt wie die Weltbevölkerung. Die weit verbreitete Mobiltelefon-Nutzung erfordert eine laufende Anpassung des Netzwerks, um die technologischen Anforderungen neuer Gerät zu erfüllen. Inzwischen konnte eine Verlagerung von ursprünglichen Funktionen, wie Text-Nachrichten und Telefonie, hin zu drahtlosem Internetzugang durch Mobiletelefone festgestellt werden; dabei wird erwartet, dass dieser Trend weiter stark zunimmt. Insgesamt bedeuten diese technologischen Fortschritte eine grundlegende Veränderung hinsichtlich der Exposition durch hochfrequente elektromagnetische Felder (HF-EMF) und führen folglich zu erhöhter Besorgnis in der Bevölkerung über mögliche gesundheitsschädigende Effekte. Einzelne Länder implementierten deshalb Grenzwerte, um die Exposition vorsorglich zu reduzieren. Bis anhin existieren jedoch keine Studien, die den tatsächlichen Einfluss solcher Vorsorge-Grenzwerte auf die Exposition in Outdoor-Bereichen untersuchen. Die Forschungsagenda der Weltgesundheitsorganisation (WHO) klassifizierte das Monitoring von HF-EMF als einen dringlich zu untersuchenden Forschungsschwerpunkt. Messgeräte, welche es erlauben, die persönliche HF-EMF Belastung zu quantifizieren, existieren erst seit einigen Jahren. Es wurden bis dato diverse Studien mit persönlichen Messgeräten (Exposimeter) durchgeführt, bei denen es den dafür rekrutierten Studienteilnehmer jedoch meistens erlaubt war, das eigene Mobiltelefon zu verwenden. Dies kann die Interpretation der Daten beeinträchtigen, wenn die Expositionsquellen differenziert untersucht und die Exposition des eigenen Mobiltelefons und die Hintergrundbelastung anderer Mobiltelefone unterschieden werden sollen.

Bis anhin ist wenig bekannt über die Expositions-Situation im Alltag und wie sich HF-EMF über die Zeit hinweg ändern. Expositions-Abschätzungsstudien sind ausserdem anspruchsvoller geworden aufgrund der hohen räumlichen und zeitlichen Variabilität von HF-EMF, was die Frage nach der Reproduzierbarkeit von persönlichen Messungen aufwirft.

Ziele

Die vorliegende Dissertation behandelt methodologische und inhaltliche Fragestellungen. Aus methodologischer Perspektive wurde der Einfluss des eigenen Mobiltelefons auf persönliche Messungen untersucht. Da unsere Messungen auf repetierenden Datenerhebungen basieren, gemäss vordefinierten Zeiten und festgelegten Messabfolgen, wurde weiter die Reproduzierbarkeit von persönlichen HF-EMF Messungen mit einem Exposimeter geprüft. Ferner wurde erforscht, wie sich das Mobilfunkbasisstation-Netzwerk auf die Exposition der Bevölkerung auswirkt. Inhaltliche Fragestellungen fokussierten auf die Charakterisierung und Quantifizierung der HF-EMF Belastung in typischen Umgebungen im Alltag und wie sich die Exposition über die Zeit änderte.

Methoden

Messungen wurden in Zeitfenstern von 3 Wochen bis zu einem Jahr in verschiedenen Umgebungen und diversen europäischen Städten (Basel (Schweiz), Amsterdam (Niederlanden), Ghent und Brüssel (Belgien))durchgeführt. Wir verwendeten ein tragbares Exposimeter für die Messungen, welches es erlaubt, die relevanten Frequenzen zwischen Radio FM (Frequenzmodulation, 88 MHz) bis WLAN (Wireless Local Area Network, 2.5 GHz) zu quantifizieren, mitsamt aller Telekommunikations-Frequenzen: GSM 900 (Global System for Mobile Communications), GSM 1800 und UMTS (Universal Mobile Telecommunications System). Die Telekommunikationsfrequenzen wurden sowohl im Uplink- (Kommunikation vom Mobiltelefon zu der Mobilfunkbasisstation) als auch im Downlink-Bereich (Kommunikation von der Mobilfunkbasisstation zum Mobiltelefon) erfasst. Wir berücksichtigten unterschiedliche typische alltägliche Umgebungen, einschliesslich Outdoor-Bereiche, öffentliche Verkehrsmittel und Innenräume.

Resultate

Bezüglich der methodologischen Fragestellungen wurde gezeigt, dass das eigene Mobiltelefon im Ruhemodus (stand-by) verglichen mit einem ausgeschalteten Mobiltelefon erhöhte Expositionswerte bis zu einem Faktor von 100 verursachte. Die

Resultate waren deutlicher während Autofahrten als während Fahrten mit öffentlichen Verkehrsmitteln, da die Hintergrundbelastung relativ hoch war, insbesondere in Zügen. Die Untersuchung der Reproduzierbarkeit von persönlichen Messungen mit einem Exposimeter demonstrierte, dass die Expositionswerte von Mobilfunkbasisstationen in Outdoor-Bereichen hochgradig reproduzierbar waren. Die Varianzanalyse (ANOVA: Analysis of Variance) zeigte, dass die Art des Gebiets (30%) und die Stadt (50%) den grössten Teil der Datenvariabilität erklärten. Typische Expositionswerte durch die Strahlung von Mobilfunkbasisstationen in Outdoor-Bereichen und verschiedenen europäischen Städte lagen zwischen 0.22 V/m in Basel und 0.43 V/m in Amsterdam. Spitzenwerte erreichten Belastungen von 0.82 V/m (Amsterdam) für das 95. Perzentil und bewegten sich zwischen 0.81 V/m (Basel) und 1.20 V/m (Brüssel) für das 99. Perzentil. Bei allen Messungen waren die höchsten Gesamtbelastungen konsistent in Zügen nachzuweisen mit Expositionswerten zwischen 0.83 V/m (Ghent) und 1.06 V/m (Brüssel), wie auch im Stadtzentrum: 0.32 V/m (Ghent) bis 0.58 V/m (Brüssel). Die Studienresultate suggerieren eine Zunahme der Gesamtbelastung durch HF-EMF in allen Gebieten kombiniert um 20% in Ghent, 38% in Brüssel und um 57% in Basel während eines Jahres zwischen April 2011 und März 2012.

Schlussfolgerungen und Ausblick

Exposimeter ermöglichen die Erfassung der Exposition in unterschiedlichen typischen Umgebungen und zeitlichen Verläufen. Solche Geräte erlauben die Erhebung einer beträchtlichen Anzahl an Messdaten mit relativ wenig Aufwand und gestatten es, eine Vielzahl von typischen Umgebungen einzuschliessen, wie öffentliche Verkehrsmittel und Innenräume.

Darüber hinaus zeigte unsere Studie, dass die Messungen der Exposition von Mobilfunkbasisstationen in hohem Masse reproduzierbar sind. Dies ist von besonderer Bedeutung, wenn Expositions-Abschätzungsstudien geplant sind, die auf repetitiven Messungen basieren.

Bei persönlichen Messungen ist es empfehlenswert, das eigene Mobiltelefon auszuschalten, da unsere Ergebnisse zeigten, dass dieses einen erheblichen Einfluss auf die persönlichen Messdaten hat. Den grössten Einfluss auf die gesamte Expositionsbelastung durch HF-EMF haben Telekommunikationstechnologien, insbesondere Mobiltelefone und Mobilfunkbasisstationen, welche die wichtigsten

Quellen der Exposition in Outdoor-Bereichen, öffentlichen Verkehrsmitteln und Innenräumen darstellen. Alle Expositionswerte lagen deutlich unter den Referenzwerten (41-61 V/m), welche von der Internationalen Kommission für den Schutz vor nichtionisierender Strahlung (ICNIRP: International Commission on Non-Ionizing Radiation Protection) empfohlen werden, sowie unter den nationalen gesetzlich implementierten Vorsorge-Grenzwerten der verschiedenen Länder (diese liegen durchschnittlich zehnmal tiefer als die ICNIRP-Referenzwerte). Darüber hinaus gab es in unserer Studie keinen Hinweis darauf, dass die Senkung der gesetzlichen Grenzwerte zu unabsichtlich höheren Expositionswerten durch die Strahlung von Mobilfunkbasisstationen führt. Eine Überwachung der Exposition der HF-EMF Belastung ist heutzutage wichtig, da laufend neue Technologien und neue Geräte mit unterschiedlichen Expositionscharakteristiken eingeführt werden. Monitoring-Studien sollen Ansätze liefern für die Untersuchung der zeitlichen Dynamik von HF-EMF und erlauben es, Gebiete mit kritischen Expositionswerten zu identifizieren. Solche Studien tragen zum besseren Verständnis von potenziell gesundheitsschädigenden Effekten bei. Forschung im EMF Bereich ist dringend erforderlich, auch hinsichtlich der Implementierung öffentlicher Massnahmen. In Anbetracht der derzeitigen Unsicherheiten, insbesondere für die Langzeitwirkung von EMF im Niedrigdosis-Bereich, ist eine Minimierung der Exposition angemessen.

Samenvatting

Inleiding en doelstellingen

De laatste twee decennia worden gekenmerkt door de introductie en sterke groei van nieuwe telecommunicatietechnologie. Vandaag is mobiele telefonie alomtegenwoordig; In 2013 zijn er circa 6.8 miljard mobiele abonnementen, bijna net zoveel als de gehele wereldbevolking. Om aan de vereisten van dit wijdverbreide gebruik van mobiele telefonie te voldoen dringt een uitbreiding van de huidige draadloze netwerken zich op. Tezelfdertijd is er een verschuiving van het gebruik van mobiele apparaten voor tekstberichten (sms) en gesprekken naar het maken van internetconnecties via mobiele apparaten. De komende jaren zal deze trend zal zich doorzetten. Al deze ontwikkelingen hebben geleid tot een substantiële wijziging van de radiofrequente elektromagnetische velden (RF-EMV) en zorgen voor bezorgdheid bij de bevolking over mogelijke nadelige gevolgen voor de gezondheid. Sommige landen voerden daarom, als voorzorgsmaatregel, strengere blootstellingslimieten in om de blootstelling van de bevolking te verminderen. Er is echter geen studie die de consequenties van een dergelijke voorzorgsmaatregel op de blootstellingsniveaus buitenshuis onderzoekt. Meetapparatuur om de persoonlijke RF–EMV blootstelling op te meten is slechts sinds enkele jaren beschikbaar. Deze persoonlijke meetapparatuur (exposimeters) wordt al in verschillende studies gebruikt om metingen uit te voeren. Meestal mochten de deelnemers in deze studies hun eigen mobilofoon gebruiken. Dit bemoeilijkt de interpretatie van de meetgegevens omdat geen onderscheid gemaakt kan worden tussen de blootstelling van de eigen mobilofoon en van de blootstelling van de mobilofoon van anderen. Tot nog toe is er weinig bekend over de blootstelling aan RF-EMV in ons dagelijks leven en hoe deze verandert in de tijd. Blootstellingsbeoordeling is zeer uitdagend vanwege de grote spatiale en temporele variabiliteit van RF-EMV, daarom vragen onderzoekers zich ook af hoe reproduceerbaar persoonlijke blootstellingsmetingen zijn.

Doelstellingen

Dit proefschrift onderzoekt zowel methodische als probleemspecifieke onderzoeksvragen. Vanuit methodologisch oogpunt, proberen we om het effect van de eigen mobiele telefoon op persoonlijke metingen te onderzoeken. Al onze metingen zijn gebaseerd op een herhaalde sequentie van datacollectie op vaste tijdstippen. Met een vooraf vastgelegde meetprocedure onderzoeken we de reproduceerbaarheid van persoonlijke RF-EMV metingen met behulp van exposimeters in de tijd. Verder onderzoeken we hoe het mobiele netwerk de blootstellingssituatie buitenshuis beïnvloedt. De probleemspecifieke onderzoeksvragen zijn gericht op het karakteriseren van RF–EMV blootstellingsniveaus in typische alledaagse omgevingen en hoe de blootstelling verandert in de tijd.

Methodes

De RF-EMV metingen worden uitgevoerd gedurende verschillende tijdsperioden gaande van 3 weken tot 1 jaar in verschillende omgevingen en in Europese steden: Basel (Zwitserland), Amsterdam (Nederland), Gent en Brussel (België). We gebruiken persoonlijke meetapparatuur (exposimeter) voor het kwantificeren van de RF-EMV blootstelling voor alle relevante frequentiebanden variërend van FM (frequentie gemoduleerde radio, 88 MHz) tot en met WLAN (Wireless Local Area Network, 2.5 GHz), met inbegrip van alle signalen voor telecommunicatie: GSM 900 (Global System for Mobile Communications), GSM 1800 en UMTS (Universal Mobile Telecommunications System) voor zowel uplink (UL, communicatie de gebruiker naar het basisstation) als downlink (DL, communicatie van het basisstation naar de gebruiker) verkeer. We onderzoeken verschillende typische alledaagse omgevingen waaronder: openbare plaatsen buitenshuis, openbaar vervoer en binnenshuis.

Resultaten

De resultaten van het methodologisch onderzoek tonen ten eerste aan dat de eigen mobilofoon in stand-by toestand blootstellingsniveaus bereikt tot een factor 100 hoger dan een mobilofoon die uitgeschakeld is. Deze resultaten zijn onmiskenbaartijdens autoritten of ritten met het openbaar vervoer (vooral treinritten). Een analyse van de reproduceerbaarheid van persoonlijke metingen met exposimeters, waarbij “analysis of variance” (ANOVA) gebruikt werd, toont aan dat de bepaling van de blootstelling door basisstations buitenshuis zeer reproduceerbaar is, ondanks de grote spatiale variatie. Deze wordt het best verklaard door het type gebied (30%) in stedelijke omgeving en de aard van de beschouwde stad (50%). Buitenshuis varieert de typische basisstationblootstelling in verschillende Europese steden tussen 0.22 V/m in Basel en 0.43 V/m in Amsterdam. De maximale opgemeten 95ste percentiel van de blootstellingsniveaus bedraagt 0.82 V/m (Amsterdam). De 99ste percentiel komt overeen met waarden die liggen tussen 0.81 V/m (Basel) en 1.20 V/m (Brussel). De Analyses van de probleemspecifieke onderzoeksvraag tonen aan dat consequent de hoogste totale RF-EMV niveaus optreden in treinen, met blootstellingsniveaus tussen 0.83 V/m (Gent) en 1.06 V/m (Brussel), en in de binnenstad, 0.32 V/m (Gent) en 0.58 V/m (Brussel). De totale RF-EMV blootstelling in all buitenomgevingen samen steeg met 20% in Gent, 38% in Brussel en 57% in Basel gedurende de studieperiode van 1 jaar tusen april 2011 en maart 2012.

Discussie en toekomst

In het kader van het karakteriseren van blootstelling aan RF-EMV, blijkt het haalbaar om met persoonlijke exposimeters de blootstelling te kwantificeren en temporele trends te onderzoeken. Exposimeters laten toe om grote hoeveelheden gegevens te verzamelen met beperkte inspanningen en bieden de mogelijkheid om een grote hoeveelheid verschillende omgevingen te onderzoeken. Bovendien toont studie aan dat de metingen zeer reproduceerbaar zijn voor de basisstationblootstelling in stedelijke gebieden buitenshuis. Dit pleit voor het plannen van blootstellingbeoordelingsstudies op basis van herhaalde metingen. Gedurende de metingen is het aanbevolen om de eigen mobilofoon uit te schakelen aangezien onze resultaten een aanzienlijke impact vertonen van de eigen mobilofoon op persoonlijke metingen. De totale RF-EMV blootstelling wordt voornamelijk bepaald door de opgemeten telecommunicatie-technologieën, i.e., mobilofoons en basisstations voor mobiele telefonie. Buitenshuis, in het openbaar vervoer en binnenshuis zijn deze de belangrijkste bronnen van blootstelling. Alle blootstellingsniveaus liggen ver onder de frequentie-afhankelijke referentieniveaus (41-61 V/m) van de internationale commissie voor niet-ioniserende stralingsbescherming (ICNIRP), alsook onder de nationale voorzorgslimieten van de verschillende landen (die gemiddeld tien keer lager zijn dan de ICNIRP referentieniveaus). Verder levert ons onderzoek geen aanwijzingen dat het verlagen van de blootstellingslimieten resulteert in hogere basisstation blootstellingsniveaus, studies met meer steden met verschillende limieten zijn echter nodig in de toekomst. Controle en metingen van de blootstelling aan RF-EMV is belangrijk, vooral met de introductie van nieuwe technologieën en de toename van de mobiele telefonie. Controlerende studies moeten verduidelijken hoe de RF-EMV blootstelling verandert in de tijd en laten toe om gebieden met hogere blootstellingswaarden identificeren. Deze studies kunnen bijdragen tot een beter inzicht in mogelijke nadelige gevolgen voor de gezondheid. Wereldwijde onderzoeksinspanningen zijn zeker nodig om de bevindingen naar het openbaar beleid te vertalen. In het licht van de huidige onzekerheden omtrent schadelijke effecten voor de gezondheid als gevolg van een langdurige lage blootstellingsdosis, zou het minimaliseren van de blootstelling acceptabel kunnen zijn.

1 Introduction and background

This thesis describes recently conducted research in the field of environmental epidemiology dealing with radiofrequency electromagnetic field (RF-EMF) exposure in everyday environments across different European cities.

1.1 What are radiofrequency electromagnetic fields (RF-EMF)?

The electromagnetic spectrum is subdivided into ionizing and non-ionizing radiation. These types of radiation are differentiated by their physical and natural effects. Ionizing radiation is caused when electrons are released from an atomic structure and thus induces damage to the desoxyribonucleic acid (DNA), whereas non-ionizing radiation causes vibration of molecules (Levy et al., 2006). Electromagnetic fields (EMFs) are part of the non-ionizing radiation of the electromagnetic spectrum (Figure 1) and can be subdivided into low-frequency (LF; up to 10 MHz) and radio-frequency (RF; 10 MHz-300 GHz) EMFs. One of the main characteristics to classify EMFs is the frequency (unit: Hz), where 1 Hz corresponds to 1 oscillation per second, and the corresponding wave length (Figure 1).

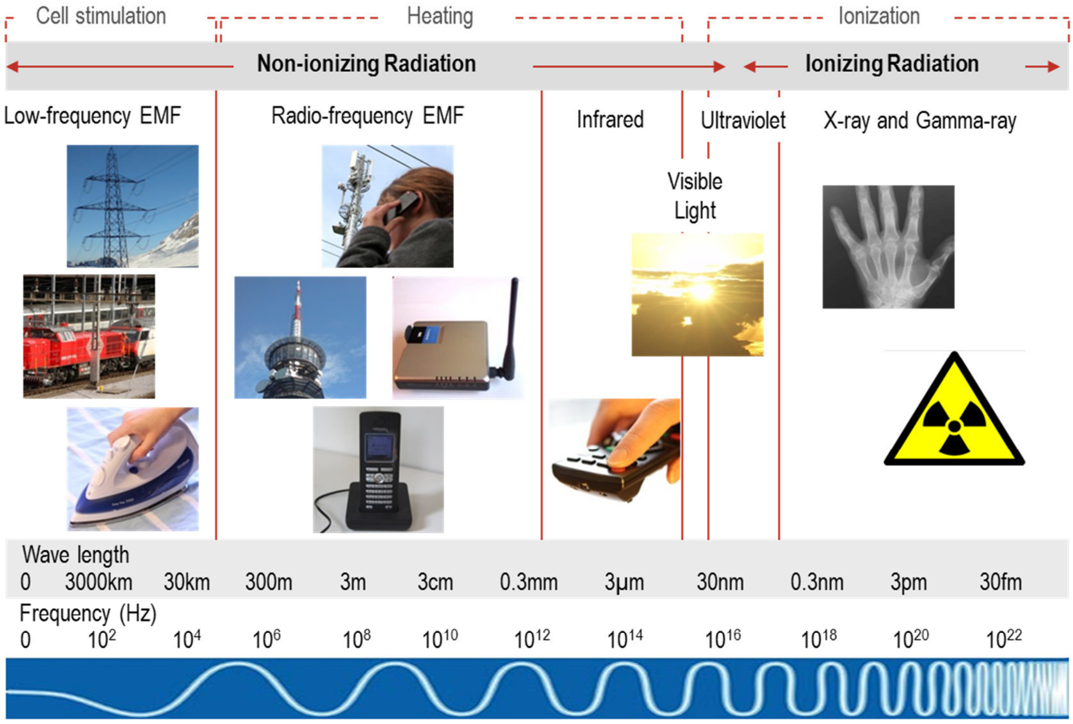

Figure 1: The electromagnetic spectrum.

EMFs arise because of the interaction between electric and magnetic fields as illustrated in Figure 2 (Tipler and Mosca, 2004).

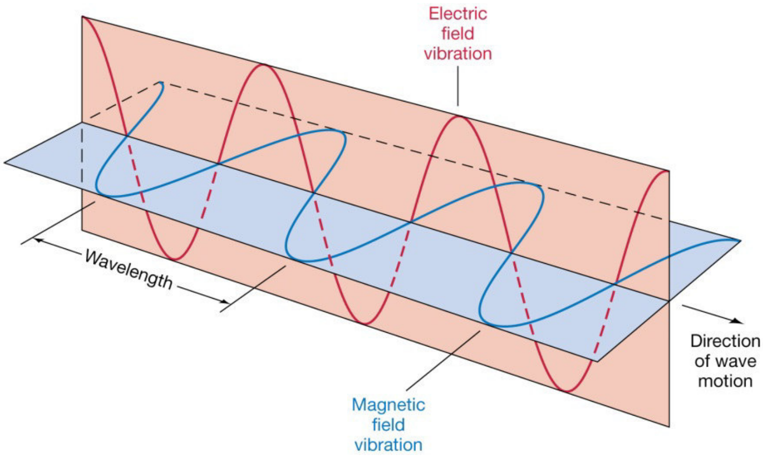

Figure 2: Propagation of a wave with electric and magnetic field vibrations. (Source: http://www2.astro.psu.edu/users/cpalma/astro10/class5.html, accessed on 4.11.2013)

The strength of EMFs can be measured using the electric field strength (E), whereby the unit is expressed in Volt per meter (V/m), or using the power flux density (S), measured in Watt per square meter (W/m^2). These two units can be converted into the other using the formula in Equation 1. The free space impedance, Z_0, is a physical constant describing the property of wave propagation through the air and is approximately 377 Ω (Levy et al., 2006). There is a quadratic relationship between the two measurement scales, E and S, as given in Equation 1.

$$E = \sqrt{S \times Z_0} \qquad \text{and} \qquad S = \frac{E^2}{Z_0}$$

Equation 1: Formulas for calculating the electric field strength (E) and the power flux density (S).

Basically, there are two sources of EMFs, i) natural sources such as the static field of the earth and ii) human-made sources, for example the emission of RF-EMFs from mobile phone base stations and broadcast transmitters. A measure of dose for RF energy is the specific absorption rate (SAR), which is defined as the power (W) which is absorbed per 1 kg tissue (Moulder et al., 2005). EMFs are specifically used in the field of information technology; typical sources and applications as well as characteristics of RF-EMFs are presented in the following sub-chapter.

1.2 Characteristics of radiofrequency electromagnetic fields

Radio-frequency electromagnetic fields are used in telecommunication technologies to transfer wireless information over long distances between a transmitter (e.g. mobile phone base stations and broadcast transmitters) and a receiver (e.g. mobile phone handsets, televisions and radios). Depending on the direction of the signal, a distinction will be made between downlink and uplink exposure, where downlink exposure represents the communication from a mobile phone base station to a mobile phone handset and uplink exposure vice versa. The most relevant frequencies are listed in Table 1 and range between Radio FM (frequency modulation, 88 MHz) to WLAN (Wireless Local Area Network, 2.5 GHz) signals, including all uplink and downlink telecommunication frequencies, i.e. GSM (Global System for Mobile Communications) and UMTS (Universal Mobile Telecommunications System).

Source	Frequency range (MHz)	Description
FM	88 – 108	Frequency Modulation Radio broadcast
TV3	174 – 223	Television broadcast
TV4&5	470 – 830	
TETRAPOL	380 – 400	Professional radio communication standard for emergency units.
GSM 900 uplink	880 – 915	Global System for Mobile Communications
GSM 900 downlink	825 – 960	
GSM 1800 uplink	1710 – 1785	
GSM 1800 downlink	1805 – 1880	
DECT	1880 – 1900	Digital Enhanced Cordless Telecommunications
UMTS uplink	1920 – 1980	Universal Mobile Telecommunications System
UMTS downlink	2110 – 2170	
WLAN	2400 – 2500	Wireless Local Area Network

Table 1: Most relevant RF-EMF frequency signals and their characteristics.

In everyday life, exposure sources to RF-EMFs can be basically classified into near-field and far-field sources. *Near-field sources*, such as mobile phone handsets and cordless phones operate near the body and can cause up to 100 times higher exposure values than far-field sources (Figure 3). The maximal energetic local absorption in the head is approximately 1'000 to 100'000 times higher during calls when compared to far-field sources (Lauer et al., 2013). With increasing distance to a source, the power flux density decreases ideally inversely proportional to the square of the distance: $1/r^2$. *Far-field sources* are defined as "radiation from a source located at a distance of more than one wavelength" (Röösli et al., 2010a). Representative sources are mobile phone base stations and broadcast transmitters, but mobile phones of nearby persons also account for far-field sources in this context. Far-field sources cause markedly lower exposure levels than near-field sources, however the whole body is continuously exposed and the duration of exposure can be strikingly longer (Frei et al., 2009a; Röösli et al., 2010b). Exposure levels from wireless internet (WLAN) sources can be regarded as near- and far-field exposure, depending on position and distance to the human body.

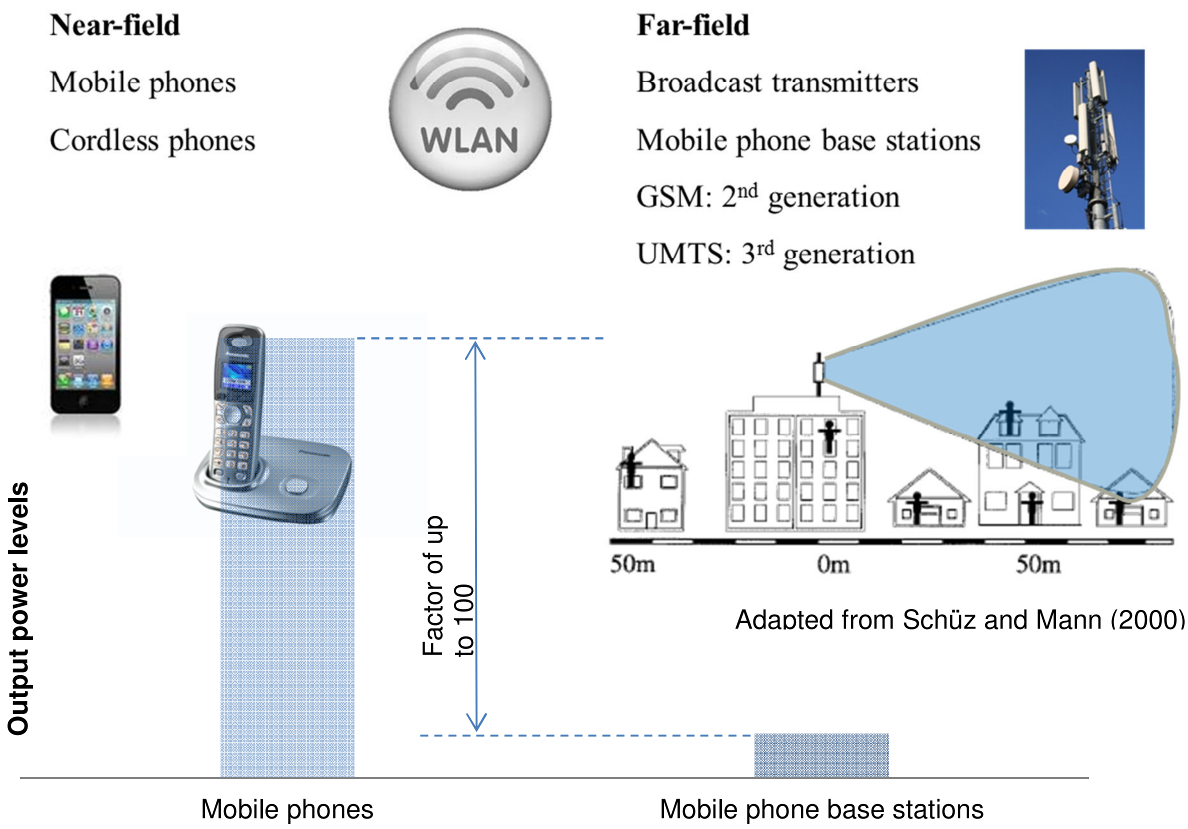

Figure 3: Near-field and far-field sources, illustrating differences of output power levels.

Exposure from mobile phone base stations causes lower RF-EMF levels but is constant over time. In contrast, exposure from mobile phone handsets radiate with up to 100 times higher levels, people, however, are exposed only during short times, e.g. while calling. Exposure patterns are complex, and several factors, such as distance and radiation intensity, influence the exposure situation. People are ubiquitously and constantly exposed to non-ionizing radiation for extended periods of time. Consequently, guidelines for limiting exposure to RF-EMFs have been elaborated following systematic reviews of the scientific literature in this area of research.

1.3 Draw the line – Regulatory RF-EMF exposure limits

The International Commission on Non-Ionizing Radiation Protection (ICNIRP), a publicly funded body of independent scientific experts, proposed and published guidelines for limiting RF-EMF exposure everywhere where people reside (ICNIRP, 1998). ICNIRP reference levels are frequency-dependent and are 41 V/m for 900 MHz, 58 V/m for 1800 MHz and 61 V/m for 2100 MHz (Table 2). The stated reference levels rely on epidemiological and experimental studies investigating adverse health effects caused by RF-EMFs. Indications based on experimental studies suggest that EMFs producing a whole-body SAR between 1 and 4 W/kg result in an increase in temperature of less than 1°C. SAR values exceeding 4 W/kg from more intense fields can cause irreversible effects, compromising thermoregulatory processes and lead to injurious tissue heating (ICNIRP, 1998). The EMF project of the World Health Organization (WHO) established a database with worldwide standards (http://www.who.int/docstore/peh-emf/EMFStandards/who-0102/Worldmap5.htm, accessed on 4.11.2013). There is a large disparity among countries regarding their regulatory limits implemented in their laws. A crucial question arises when talking about safety of unknown risks: how safe is safe enough (Fischhoff et al., 1978)? Several countries adopted ICNIRP reference levels, as for example the Netherlands, whereas other countries like Switzerland and Belgium additionally introduced frequency-dependent precautionary exposure limits (Table 2). One important reason for applying precautionary limits was explained by the WHO (Wiedemann et al., 2013):

> *"To address public health concerns that a potential or perceived but unproven health problem is taken into account..." (WHO 2003, p. 3)*

In Switzerland, the ordinance related to protection from non-ionizing radiation[1] (ONIR) has the purpose to protect people against potential adverse health effects or nuisances caused by non-ionizing radiation (ONIR, 1999). The ONIR limits apply to the radiation from one single base station and are only relevant for sensitive areas where persons spend most of their time, such as residences, schools, kindergartens, hospitals, nursing homes, workplaces, and playgrounds. In Belgium, even more stringent limits are imposed than in Switzerland. In Ghent, exposure limits of the Flemish region (Resolution[2] of the Flemish Region of Nov. 2010) regulate a frequency-dependent cumulative exposure of 21 V/m for 900 MHz frequency, whereas in indoor places and children's playgrounds limits of 3 V/m at 900 MHz, 4.2 at 1800 MHz and 4.5 V/m at 2100 MHz are valid per base station. These precautionary limits are estimated following equation 2 for the frequency range between 400 MHz and 2 GHz.

$$E = 0.1 * \sqrt{f}$$

Equation 2: Formula for calculation of frequency-dependent precautionary limits per base station. With *f* as the frequency in Hz and *E* as the electric field strength in V/m.

For the frequency range between 2 GHz to 10 GHz a limit of 4.5 V/m is imposed. In Brussels, the most stringent limits are in the Brussels Capital Region (Ordinance[3] of the Brussels Capital Region of 14 March 2007) and are implemented and valid at all public places for cumulative exposure. For frequencies between 400 MHz and 2 GHz, limits are calculated using the formula in equation 3.

$$S = \frac{f}{40{,}000} \quad \text{and} \quad E = \sqrt{\frac{f}{40{,}000} * 377}$$

Equation 3: Regulatory frequency-dependent limits for cumulative exposure for frequencies between 400 MHz and 2000 MHz. With *f* as the frequency in Hz, S (power flux density) with the unit W/m^2 and E (electric field strength) with the unit V/m.

For frequencies between 2 GHz and 300 GHz, exposure values may not exceed 4.3 V/m (corresponds to 0.05 W/m^2 on power flux density level). The limits in Brussels

[1] Ordinance of 23 December 1999 relating to Protection from Non-Ionizing Radiation (ONIR), SR 814.710.

[2] Resolution of the Flemish Government of 23 January 2010.

[3] Resolution of the Brussels Capital Region of 14 March 2007 and active from March 2009.

Capital Region will be adapted to enable the introduction of 4G (Long-term Evolution, LTE) in Brussels.

Frequency	ICNIRP reference levels	The Netherlands	Precautionary limits for places with sensitive use and places of residence		
			Switzerland	Ghent (Belgium)	Brussels (Belgium)
GSM 900	42 V/m	42 V/m	4 V/m	3 V/m	2.9 V/m
GSM 1800	58 V/m	58 V/m	6 V/m	4.2 V/m	4.1 V/m
UMTS	61 V/m	61 V/m	6 V/m	4.5 V/m	4.3 V/m

Table 2: Overview of the different limits adopted in Switzerland, Belgium and the Netherlands (Source: Federal Office for the Environment (FOEN), Resolution of the Flemish Government[2] and Resolution of the Brussels Capital Region[3]).

1.4 Wireless mobile telecommunication – past and present

Since the introduction of mobile telecommunication in Europe, the US and Japan in the second half of the 20th century, there has been an extensive, sustained development and dispersal of mobile phone handsets (Dunnewijk and Hultén, 2007).

"I'm ringing you just to see if my call sounds good at your end."
(Martin Cooper, Motorola employee; statement after the first mobile call in New York, 3rd April 1973)

According to the latest published data of the International Telecommunication Union (ITU, 2013, source: http://www.itu.int/en/ITU-D/Statistics/Pages/stat/default.aspx, accessed on 4.11.2013), it is estimated that there are approximately 6.8 billion mobile phone subscriptions worldwide (ITU, 2013, data of 2013), accounting for 1.6 billion mobile phone subscriptions in the developed world and 5.2 billion subscriptions in the developing world. In 2012 mobile data traffic grew by around 70% (CISCO, 2013). By the end of 2012, 10.5 million mobile phone subscriptions were registered in Switzerland (Figure 4). In developing countries, represented by Tanzania in Figure 4, there has been a strong increase since 2005.

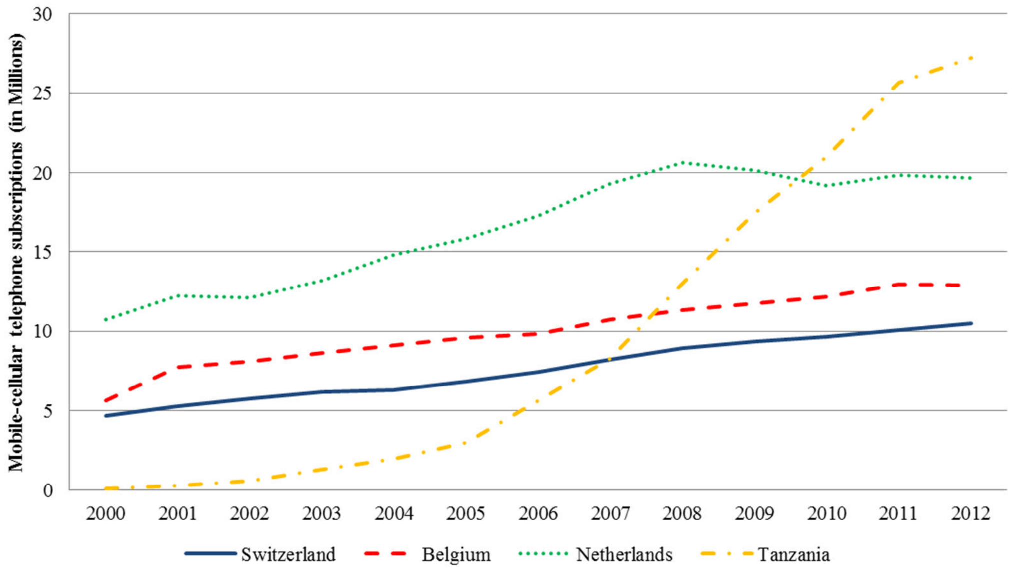

Figure 4: Development of mobile-cellular telephone subscriptions from 2010 to 2012 (ITU, 2013) in Switzerland, Belgium, the Netherlands and Tanzania.

A feature introduced by second generation mobile phones (2G, GSM) is the adaptive power control (APC): starting with maximal output power and down-regulate the output power over time, after the establishment of a connection (Lönn et al., 2004). In contrast, third generation mobile phones (3G, UMTS) use an enhanced APC with 100 to 1'000 times lower average output power radiation resulting in 1% of the maximum (Gati et al., 2009; Kelsh et al., 2011; Persson et al., 2011; Wiart et al., 2000). In addition, quad-band phones (3G), so-called smartphones, allow accessing mobile internet through a variety of web-based applications, such as mobile television, push notifications for e-mails, breaking news and much more.

To meet the requirements of new mobile phone handsets, especially smartphones, new technologies and frequencies had to be implemented over the last few years. After the second and the third radio standard, the fourth technology (4G) known as Long-term Evolution (LTE) is gradually employed in several cities. LTE has a 3 to 4 times higher spectrum efficiency as UMTS/HSPA (High Speed Packet Access) (BAKOM, 2013). LTE is allocated on 800 MHz, 1800 MHz (in France and Belgium) and 2.6 GHz frequencies. With LTE, it is possible to reach and even surpass data rates of 100 Mbit/s with maximal data rates of up to 326 Mbit/s on the downlink and 86 Mbit/s on the uplink (BAKOM, 2013).

1.5 Potential health implications

Discussions on health effects of RF-EMFs are filled with controversy. In May 2011, the International Agency for Research on Cancer (IARC) classified RF-EMF as possibly carcinogenic to humans, representing category 2B (Baan et al., 2011).

The most exposed part of the body to RF-EMFs is the head during the use of mobile phones. Thus, it is assumed that potential adverse health effects in terms of carcinogenicity would manifest most likely tumours in the region of the head. Of primary concern are different types of tumours of the brain (glioma and meningioma), acoustic nerve (schwannoma, also known as acoustic neuroma) and parotid gland (Baan et al., 2011; IARC, 2010). Various studies have been conducted in order to address the research question whether the use of mobile phone is associated with potential adverse health effects. One of the largest studies was the INTERPHONE study, coordinated by the WHO. It is an interview-based case-control study, including 2708 glioma and 2409 meningioma cases and matched controls across 13 countries using a common protocol (INTERPHONE study group, 2010).

Overall, there was no observed increased risk associated with mobile phone use for the different types of tumours. There were some indications of a statistically significant increased risk of glioma (Odds ratio (OR[4]) = 1.40, 95% Confidence interval (CI) = 1.03 to 1.89) at the highest exposure levels for the 10th decile of the cumulative call duration (≥1640 hours), but not for meningioma (OR = 1.15, 95% CI = 0.81 to 1.62). However, the increased risk is likely attributed to selection bias and recall errors inhibiting a causal interpretation.

It has been hypothesized that children are a more vulnerable group than adults and are at higher risk as children start to use their mobile phone earlier in life and consequently have a higher cumulative lifetime exposure during (Böhler and Schüz, 2004). In children, brain tumours are the second most common type of tumours after leukaemia (Michel et al., 2007). The CEFALO multicenter case-control study investigated whether mobile phone use is associated with brain tumour risk in children and adolescents. The study compiles data from Denmark, Sweden, Norway and Switzerland, including all children and adolescents between 7 and 19 years. They found no increased risk of brain tumours for areas of the brain absorbing the highest amount of energy. Regular mobile phone users are not more likely to be

[4] Odds ratio: Measure of association between an exposure and an outcome (Szumilas, 2010).

diagnosed with brain tumours compared to non-users (OR = 1.36, 95% CI = 0.92 to 2.02). Children who started to use their mobile phone five years ago prior to the study were not at increased risk compared with non-regular users (OR = 1.26, 95% CI = 0.70 to 2.28). The authors concluded that there is no causal association with respect to an absence of an exposure-response relationship in terms of mobile phone use or localization of the brain tumour (Aydin et al., 2011).

A systematic review of the scientific literature exploring a potential association between mobile phone use and risk of brain tumours was conducted (Repacholi et al., 2012). Meta-analysis of epidemiological studies showed no statistical evidence for an increased risk for adult brain cancer or other head tumours being associated with mobile phone use. The same was found for in vivo oncogenicity, tumour promotion and genotoxicity studies analyzing damage to brain cells or incidence of brain or other types of tumours of the head (Repacholi et al., 2012).

The majority of studies scrutinizing the association between mobile phone use and brain tumours do not support a causal relationship (Ahlbom et al., 2009; Aydin et al., 2011; Frei et al., 2011; INTERPHONE study group, 2010; Repacholi et al., 2012). Due to the fact that mobile phone use increased drastically in recent years, potential risks of brain tumours should have been appeared in an increased incidence of new cases. This has not been observed so far in different countries (de Vocht et al., 2011; Inskip et al., 2010). Methodological limitations such as selection bias and retrospective questionnaire data analysis complicate interpretation and could partially explain some of the potential increases in risk found in some studies.

Apart from brain tumours, commonly described health effects are self-reported non-specific symptoms of perceived EMF defined as electromagnetic hypersensitivity or idiopathic environmental intolerance (Rubin et al., 2010). Such symptoms include headache, sleep disorders and/or impaired concentration (Hug and Röösli, 2012). There is high evidence that low levels of EMFs cannot be perceived; this has been tested in different experimental studies under double-blind and randomized conditions (Hug and Röösli, 2013; Röösli et al., 2010a). Potential effects of RF-EMFs emitted by GSM mobile phones (2G) on subjective symptoms, well-being and physiological parameters, showed little evidence for acute effects (Augner et al., 2012). Various studies concluded that there is no association between RF-EMFs and non-specific symptoms, and there are no indications of persons being able to perceive or feeling sensitive to EMFs (Hug and Röösli, 2012; Kundi and Hutter, 2009;

Röösli et al., 2010a; Röösli and Hug, 2011; Rubin et al., 2005; Rubin et al., 2010). Nevertheless, there are signs of nocebo effects. Nocebo effects are the inverse of placebo effects and are adverse events caused by negative expectations which have been examined in several studies (Augner et al., 2012; Röösli, 2008; Rubin et al., 2010). Markedly more, and stronger, symptoms appeared when patients knew to be exposed.

Impairments of subjective sleep quality was investigated in several studies (Hinrichs et al., 2005; Regel et al., 2007; Huber et al., 2002; Mohler et al., 2010). These studies showed overall no association between RF-EMF exposure and objective sleep measures (Mohler et al., 2010). Small differences for frequency bands were observed in the EEG (electroencephalography) (Mohler et al., 2010).

The current landscape of research indicates that, in the short-term (<10 years), there is no association between mobile phone use and an increase in health effects. Nevertheless, there are uncertainties for long-term and heavy use (>10-15 years). The COSMOS study (cohort study of mobile phone use and health, http://www.ukcosmos.org/, accessed on 7.11.2013) is one of the largest research studies worldwide aiming to carry out long-term health monitoring among a large group of study participants (Schüz et al., 2011).

Experimental studies analyze only acute effects, and long-term risks have to be investigated through epidemiological studies. In this context, exposure assessment is one of the major challenges, since measurement devices became available only a few years ago. In view of that, a better understanding of exposure assessment methods and characterization of exposure levels may help to clarify open research questions.

1.6 Overview of different exposure assessment methods

In general, near-field sources, such as mobile and cordless phones, and far-field sources, like mobile phone base stations and broadcast transmitters, can be differentiated as described in Chapter 1.2. Mobile phones of persons in proximity can also be considered as a far-field source, as exposure to RF-EMFs drastically decreases with increasing distance. Different measurement procedures have been developed to assess RF-EMF exposure. The most common methods are

- *Broadband probes* which allow performing a fast scanning of the environment without specifying the exact source (Figure 5, left).
- *Spectrum analyzers* are very accurate measurement devices able to differentiate between different sources as well as between different operators. Measurements are taken on a fixed position (in-situ; as illustrated in Figure 5 (middle)). In the illustrated example, the spectrum analyzer was placed in a car connected to a laptop. The probe was placed in free space and fixed on a pillar at 1.5 m height).
- *Exposimeters* are very useful and feasible portable measurement devices enabling personal measurements. They allow differentiating between different sources, including all relevant telecommunication signals (Chapter 3.2).

A comparison in terms of strengths and limitations will be presented in Chapter 9.3 of the Discussion.

Figure 5: Different measurement devices for assessing RF-EMF exposure. Broadband probe (left), spectrum analyzer (middle) and exposimeter (right).

2 State of research and objectives of the thesis

2.1 Research gaps

Mobile telephony is nowadays ubiquitous and revolutionary new wireless telecommunication devices have been introduced. With the innovation of new mobile phones, the purpose of such smartphones is focused, apart from calls and texting, more and more on web-based applications, such as mobile television (streaming), e-mail access with push notifications and alerts for breaking news and a large variety of other applications. New technologies are altering radiofrequency electromagnetic field (RF-EMF) exposure patterns. New telecommunication standards had to be implemented in order to meet the requirements of new mobile phones and to ensure a widespread coverage. Currently, the upcoming fourth technology standard (LTE) is gradually being introduced in cities across different countries worldwide. Thus, the telecommunication network had to be expanded over time (Neubauer et al., 2007), as previously described in Chapter 1.4, to satisfy on the one hand the increasing usage of mobile phones, and, on the other hand, to fulfil requirements of new mobile phones able to transfer high data rates for web-based applications. To date, it is unknown how the mobile phone base station network impacts the exposure of the population. The introduction and development of new wireless telecommunication technologies in the last two decades led to a fundamental change of the exposure situation of the population (Frei et al., 2010; Neubauer et al., 2007; Röösli et al., 2010b) regarding far-field and near-field RF-EMF sources. Characterization of spatial and temporal distribution of RF-EMFs in typical everyday environments, such as different outdoor areas, public transports or indoor settings, is scarce so far. The Research Agenda of the WHO considered monitoring studies to quantify RF-EMF exposure as a high research priority need (WHO, 2010).

Measurement devices became available only some years ago. There are several strategies and methodologies to monitor RF-EMF exposure as described in Chapter 1.6. One approach is the use of personal exposimeters, which has been applied for all our measurements. The applicability of exposimeters is highly recommended to characterize RF-EMF exposure and they have been widely used in various studies

(Bolte and Eikelboom, 2012; Bolte et al., 2011; Breckenkamp et al., 2008; Frei et al., 2010; Frei et al., 2009a; Joseph et al., 2008; Knafl et al., 2008; Neubauer et al., 2007; Thuróczy et al., 2008; Viel et al., 2009). Exposimeters allow the collection of a considerable volume of data in different environments, are of small size, and easy to use. Advantages and disadvantages of different exposure assessment methods are described in Chapter 9.3. In most studies, exposure measurements were conducted by recruited study participants, whereas it was partly allowed to use the personal mobile or cordless phone during measurements which might limit the interpretation of data if being interested to differentiate between the exposure of the own mobile phone and other people's mobile phone. Furthermore, it may happen, that study participants place the exposimeter at positions where high RF-EMFs are expected, causing unreliable exposure data. A proposed study protocol for the conduct of personal RF-EMF measurement studies was described by Röösli et al. (2010b). To date, reliable exposure assessment methods are lacking. In epidemiological studies, only crude methods have been used so far, such as self-reporting of mobile phone use (Röösli et al., 2010b). One of the major problems of previous studies aiming to compare RF-EMF exposure between countries was the use of different exposure assessment methods and different data analysis procedures, whereby observed differences might have been influenced by methodological differences (Joseph et al., 2010a; Röösli et al., 2010b).

2.2 Objectives

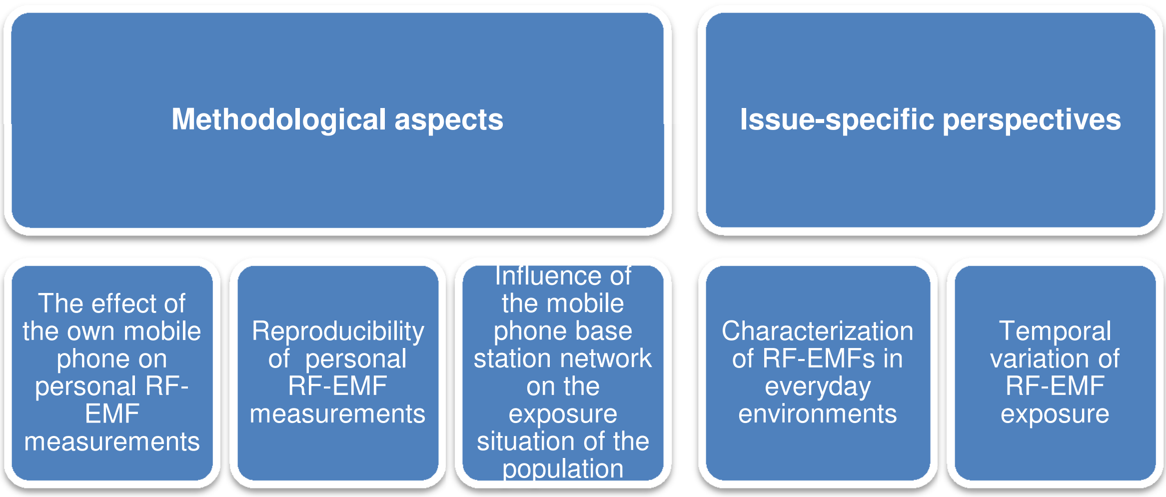

Figure 6: Overview of the different objectives addressed in this thesis.

Objective 1: The effect of the own mobile phone on personal RF-EMF measurements.

Several epidemiological studies analyzed the mobile phone use of study participants, the most common exposure surrogate in epidemiological RF-EMF research, with personal exposimeters. However, personal measurements are affected by the owner's mobile phone when measurements are conducted by study participants using their personal mobile phone. This can limit the interpretation of data if one is interested in differentiating between different exposure sources. In addition, with the introduction of smartphones, mobile phone handsets do not only radiate during calls or when texting, but also when being in stand-by mode because of updates and notifications of certain applications. This is especially relevant when the person is moving. A specific area is subdivided into different cells (location areas) which are served by one or a cluster of mobile phone base stations (Figure 7).

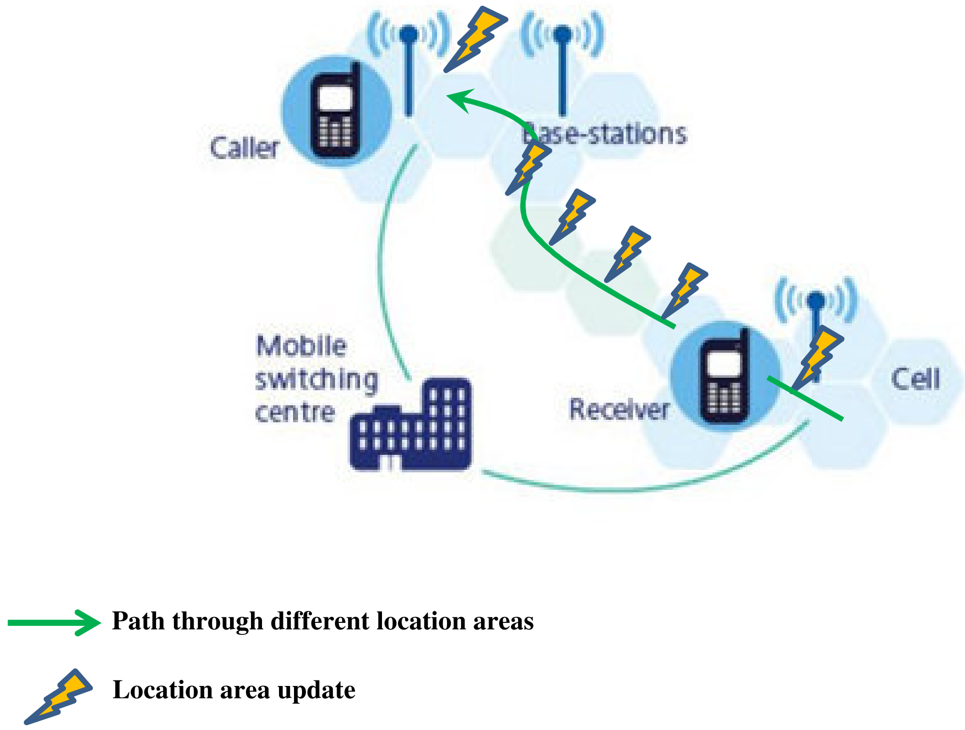

Figure 7: Overview of the location areas served by one or a cluster of mobile phone base stations (Source: adapted from http://casestudy-itgs.wikispaces.com/Terminology+-+Cell+Phone+Mobile+Phone, accessed on 14.11.2013).

When changing the location area, the mobile phone handset sends a signal to the mobile phone base station of the respective area providing information on its position with the purpose of maintaining constant connectivity (Lin et al., 2002). These activities are called '*location area updates*'. In contrast, '*handovers'* occur when changing the location area during a call. So far, it is still unclear how location area updates affect personal RF-EMF exposure and thus contribute to total RF-EMF exposure while moving.

We performed two different studies: (1) in different modes of public transportation including trains, buses, and trams and (2) in a car while driving in rural areas, on highways and in cities.

Exposure from a mobile phone handset (uplink) was measured during commuting using a randomized cross-over study with three different scenarios: disabled mobile phone (reference), an activated dual-band mobile phone of the second generation and a quad-band phone of the third generation. Presentation of the results are described in Article 1 (Chapter 4).

Objective 2: Reproducibility of personal RF-EMF measurements.

A reliable approach to measure RF-EMF exposure is the use of personal exposimeters, which has been described in several studies (Bolte and Eikelboom, 2012; Frei et al., 2009a; Joseph et al., 2010a; Thuróczy G. et al., 2008; Viel et al., 2009). A prerequisite to conduct personal measurements is the criteria of reproducibility of measurements over time. Measurements collected in the framework of this thesis are based on a measurement protocol assessing personal exposure measurements on the same days at the same times (except for objective 2) and in the same microenvironments over the study periods (Chapter 3). In this context we evaluated the reproducibility of personal exposure measurements in different outdoor urban areas of two European cities, i.e. Basel (Switzerland) and Amsterdam (the Netherlands). We considered central and non-central residential areas, downtown and business areas. Measurements were performed during three months every second week on two consecutive days at different times of the day using personal exposimeters. Results are discussed in Article 2 (Chapter 5).

Objective 3: Influence of the mobile phone base station network on the exposure situation of the population.

Concerns of the general public about potential adverse health effects caused by RF-EMFs led authorities to introduce precautionary exposure limits which are lower than the limits proposed by ICNIRP (Chapter 1.3). These vary considerably between countries and even at regional levels, as for example in Belgium. Based on the fact that along with newer wireless mobile technologies, the mobile phone base station network had and still has to be expanded, it is so far unknown whether lower regulatory limits affect the exposure of the population. The situation is complex, as lowering standard limits is expected to decrease the exposure of the population because antennas of mobile phone base stations radiate with lower output powers. Lower output powers of antennas, in turn, may be compensated on the one hand with a denser mobile phone base station network and on the other hand with lower mast height and stronger tilt. Consequently, this might increase the RF-EMF exposure of the population. So far, an evaluation examining the impact of such limits on the exposure of the general public is lacking.

In the framework of this thesis we pooled two different monitoring studies. Study 1 was conducted in Basel (Switzerland), Ghent and Brussels (Belgium) measuring RF-EMF exposure for one year on a monthly basis; study 2 was carried out in Basel (in the same areas as study one but considering different paths) and Amsterdam (the Netherlands) taking measurements every second week for three months. In all cities we included outdoor urban central and non-central residential and downtown areas. Results are illustrated in Article 3 (Chapter 6).

Objective 4: Characterization of RF-EMF exposure in everyday environments.

The introduction and development of new wireless telecommunication devices led to a substantial change of the exposure situation of the population. Exposure characterization with personal measurement devices (exposimeters) has only been possible for some years and thus, only limited data are available. Our study aimed to characterize RF-EMF exposure levels in typical everyday environments including outdoor areas, public transportations and indoor settings across different European cities, i.e. Basel, Ghent, Brussels and Amsterdam (in Amsterdam only outdoor areas were considered). Measurements were conducted using a personal exposimeter in during several periods between three months and one year. The results are presented in the Articles 3 and 4 (Chapters 6 and 7).

Objective 5: Temporal variation of RF-EMF exposure.

The ongoing change of the exposure in the course of the last 20 years due to the use of new technology standards leads to the question of how exposure has changed over time. Information about the development of RF-EMFs over time is very limited so far. Several studies investigated temporal variations of RF-EMFs on a short-term basis during one day or one week to several weeks. However, long-term variability of RF-EMFs on a yearly basis has never been examined so far. We conducted personal measurements in 3 European cities (Basel, Ghent and Brussels) over a period of one year based on a common measurement protocol. We considered typical everyday environments such as outdoor areas, public transports and indoor settings to investigate temporal trends of RF-EMFs. The results are given in Article 4 (Chapter 7).

3 Methods

3.1 Overview of the different data collection periods

Data collection has been performed during different periods across different European cities in Basel (Switzerland), Ghent and Brussels (Belgium) as well as in Amsterdam (the Netherlands). Figure 8 gives an overview about the detailed data collection periods in the respective city with the corresponding measurement days per month for each conducted study.

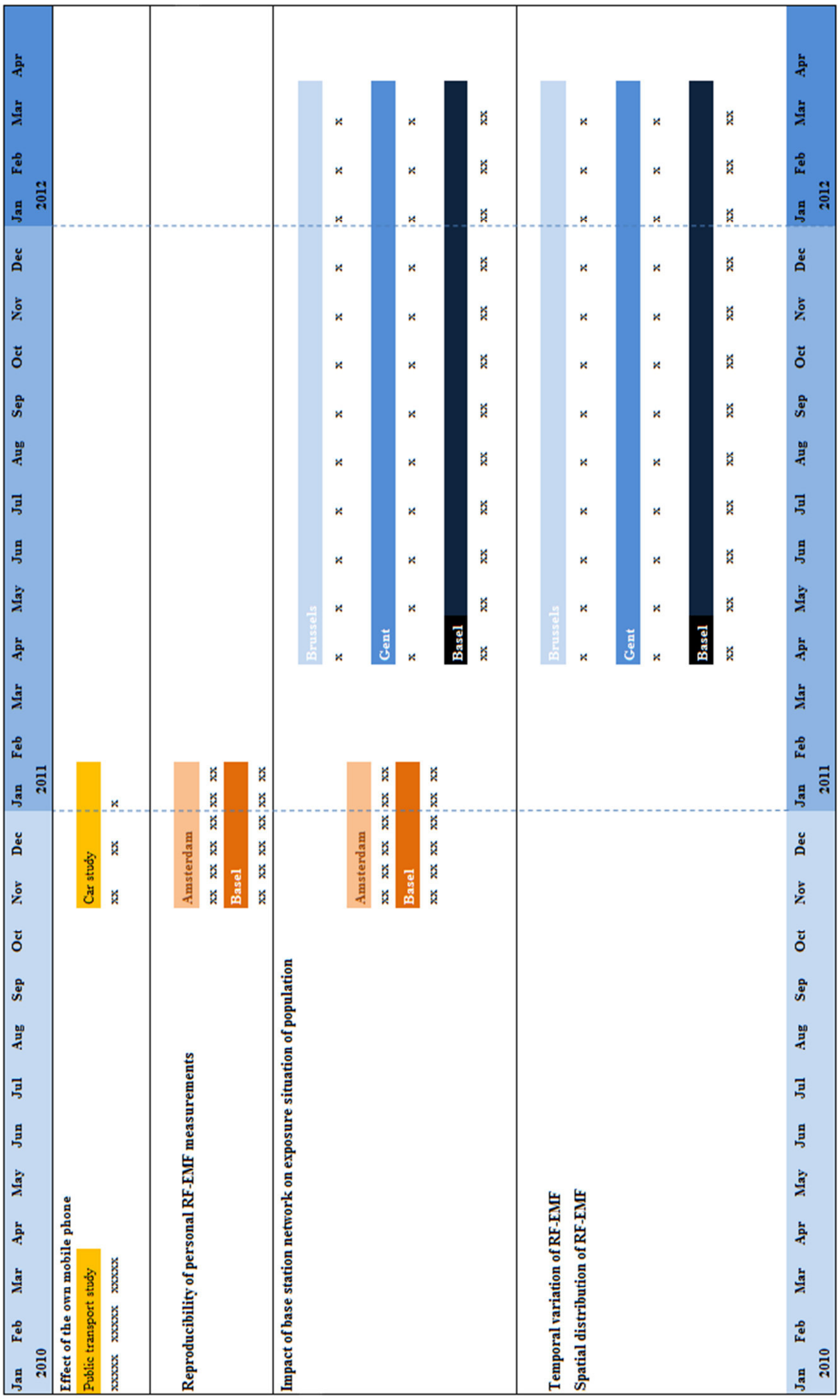

Figure 8: Overview of the measurement periods across the different European countries.

'X' Indicates the number of measurements within a month.

3.2 Personal measurement devices

We used a personal measurement device (exposimeter), specifically the EME Spy 120, to collect data (Figure 9, left). The EME Spy 140 was merely used for data collection in Amsterdam during three months (Figure 9, right).

Figure 9: Personal exposimeters of the type EME Spy 120 (left) and EME Spy 140 (right).

Such personal exposimeters are suitable to collect data in everyday environments, since they allow the collection of a substantial number of data points. Due to their comparable small size of around 19 cm height, they are well portable. The devices EME Spy 120 and 140 are capable to quantify RF-EMF exposure from 12 and 14 different sources separately, respectively, ranging from FM (88 MHz) to WLAN (2.5 GHz), including all telecommunication frequencies: GSM 900 (Global System for Mobile Communications), GSM 1800 and UMTS (Universal Mobile Telecommunication System) in up- (UL, communication from mobile phone to base station) and downlink (DL, communication from base station to mobile phone) traffic (Table 1, Chapter 1.2). The lower detection limits are 0.05 V/m for the EME Spy 120 and 0.005 V/m for the EME Spy 140, and the upper detection limit is 5 V/m for both devices. The measurement interval was always set up to 4 seconds in order to allow collecting as many data points as possible. In order to check consistency of measurements over time, all devices were calibrated in September 2010, April 2011, and December 2011 at the Swiss Federal Institute of Technology (ETH) in the laboratory of electromagnetic fields and microwave electronics.

3.3 Statistical analyses

To take into account that a large proportion of data were below the lower sensitivity levels of the device (EME Spy 120: 0.05 V/m; EME Spy 140: 0.005 V/m), we calculated daily arithmetic means per frequency band and per environment using the robust regression on order statistics (ROS) (Röösli et al., 2008; Helsel, 2005). If less than three measurements were above the detection limit, the arithmetic mean value was set to 0.01 V/m (corresponds to 0.000265 mW/m^2 on the power flux density scale). All calculations were conducted using power flux density values (i.e. power flux per environment) in W/m^2 and then back-transformed to electric field strengths values in V/m. Overall we considered three groups of combined frequencies:

a) *Total RF-EMF exposure:* sum of all frequency bands combined, excluding DECT (Digital Enhanced Cordless Telephone). DECT had to be excluded due to cross-talk[5] effects with nearby bands, i.e. GSM 1800 downlink signals.
b) *Downlink exposure (mobile phone base station exposure):* sum of mean power densities of all downlink frequencies: GSM 900 (925-960 MHz), GSM 1800 (1805-1880 MHz) and UMTS (2110-2170 MHz).
c) *Uplink exposure (mobile phone handset exposure):* sum of mean power densities of all uplink frequencies: GSM 900 (880-915 MHz), GSM 1800 (1710-1785 MHz) and UMTS (1920-1980 MHz).

3.4 Measurement protocol

We used a common data collection protocol in each city. Measurements were conducted during different time periods and collected by the same research assistant (except in Amsterdam) each time, by walking along the same routes using the same time schedules at each time instance. The measurements were assigned to the respective microenvironment using a software-based application developed by the Swiss Federal Institute of Technology (ETH) as shown in Figure 10.

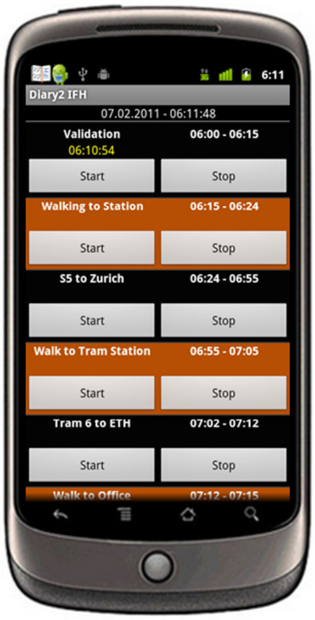

Figure 10: Software-based questionnaire for Android smartphones. In this mode the APP allows the documentation of a fixed predetermined daily routine in a time-activity diary.

[5] Cross-talk defines the presence of a signal in a nearby frequency band due to the small frequency separation between some service bands (Lauer et al., 2012).

This application can simply record start and end time during an activity by setting a marker and recording the time in the respective microenvironment. The mobile phone of the person taking the measurements was switched off and the mobile phone used as time activity diary was in flight mode preventing an influence on measurements. The smartphone saves questionnaire entries with a timestamp. Recorded data can further be downloaded and finally been linked with the data of the exposimeter by the time variable for data analysis.

4 The effect of the own mobile phone on personal RF-EMF measurements

Article 1: Impact of one's own mobile phone in stand-by mode on personal radiofrequency electromagnetic field exposure

Damiano Urbinello[1,2] and Martin Röösli[1,2]

[1] Swiss Tropical and Public Health Institute

[2] University of Basel, Switzerland

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ORIGINAL ARTICLE

Impact of one's own mobile phone in stand-by mode on personal radiofrequency electromagnetic field exposure

Damiano Urbinello[1,2] and Martin Röösli[1,2]

When moving around, mobile phones in stand-by mode periodically send data about their positions. The aim of this paper is to evaluate how personal radiofrequency electromagnetic field (RF-EMF) measurements are affected by such location updates. Exposure from a mobile phone handset (uplink) was measured during commuting by using a randomized cross-over study with three different scenarios: disabled mobile phone (reference), an activated dual-band phone and a quad-band phone. In the reference scenario, uplink exposure was highest during train rides (1.19 mW/m^2) and lowest during car rides in rural areas (0.001 mW/m^2). In public transports, the impact of one's own mobile phone on personal RF-EMF measurements was not observable because of high background uplink radiation from other people's mobile phone. In a car, uplink exposure with an activated phone was orders of magnitude higher compared with the reference scenario. This study demonstrates that personal RF-EMF exposure is affected by one's own mobile phone in stand-by mode because of its regular location update. Further dosimetric studies should quantify the contribution of location updates to the total RF-EMF exposure in order to clarify whether the duration of mobile phone use, the most common exposure surrogate in the epidemiological RF-EMF research, is actually an adequate exposure proxy.

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Keywords: radiofrequency electromagnetic fields (RF-EMF); personal exposure meters (PEM); location update; mobile phone; stand-by

INTRODUCTION

The applicability of personal exposure meters (PEM) has successfully been demonstrated in several epidemiological studies to characterize personal exposure to environmental radiofrequency electromagnetic field (RF-EMF) such as mobile phone base stations or broadcast transmitters.[1–6] It is acknowledged, however, that personal measurements are affected by one's own mobile phone use (uplink emissions), which is a severe limitation for the interpretation if one is interested in differentiating between exposure from one's own mobile phone and other people's mobile phone. Such a differentiation is important, as exposure of the body depends heavily on the distance to the source, which is different for one's own mobile phone compared with other people's mobile phone.

Mobile phones are emitting RF-EMF not only when being used for calls and texting, but also in the stand-by mode owing to its location updates; that is, changing from one cluster of base stations to the next.[7] As a network is divided into cells (location areas), covered by a group of base stations, a mobile phone informs the cellular network about changes in its location area, based on different location area codes. Such location updates are necessary to maintain constant connectivity with the network. In particular, when moving in a car or train, a mobile device periodically sends information about its position while changing location. However, little is known so far on the extent of such location updates in real-life situations.

Most personal exposure assessment studies have focussed on environmental EMF, and thus exposure from one's own mobile phone (uplink) is not of interest, and different strategies have been used to deal with that problem:[8] (1) noting wireless calls in a diary and excluding the corresponding PEM measurements from the data analysis[9] or (2) hiring people for taking measurements and forcing them to shut down their own mobile phones.[8] The latter approach is the best solution from a scientific point of view, but is unlikely to be acceptable for volunteers of a population survey.[1]

With the diary approach,[9] higher mean mobile phone uplink exposure levels for study participants owning a mobile phone compared with participants not owning a mobile phone (0.0417 *vs* 0.0189 mW/m^2, respectively) had been observed.[9] This difference may be explained by forgotten or imprecise diary entries, by difference in the behaviour between the two groups in terms of spending time close to other mobile phone users or owing to location update procedures of one's own mobile phone in stand-by mode.

To systematically evaluate the impact of one's own mobile phone in stand-by mode on PEM measurements, two measurement studies were conducted: a public transport study and a car study. As we hypothesized that the impact of one's own mobile phone is increasing with increasing movement velocity, we included measurements from different types of settings: in trains, buses and cars, while moving and staying at train and bus stations. We also considered the frequency bands, Global System for Mobile Communications (GSM) and Universal Mobile Telecommunications System (UMTS) separately, as well as the distance between the mobile phone and the PEM.

[1]Department of Epidemiology and Public Health, Swiss Tropical and Public Health Institute, Basel, Switzerland and [2]University of Basel, Basel, Switzerland. Correspondence: Dr. Martin Röösli, Department of Epidemiology and Public Health, Swiss Tropical and Public Health Institute, Socinstrasse 57, Basel 4051, Switzerland.
Tel.: +41 61 284 83 83. Fax: +41 61 284 85 01.
E-mail: martin.roosli@unibas.ch
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METHODS

Study Design

We used a three-way randomized cross-over study design with three scenarios: (i) a disabled mobile phone (reference); (ii) a dual-band mobile phone (Nokia 2600) working on two frequency ranges: GSM900 (880 – 915 MHz) and GSM1800 (1710–1785 MHz); and a quad-band smart phone (Blackberry bold 8800 and an iPhone 4) capable of transmitting and receiving on four frequency ranges: GSM900, GSM1800, CDMA (Code Division Multiple Access, 850–1910 MHz) and UMTS (1920–1980 MHz).

An overview of the study design is shown in Figure 1. During the nonreference scenarios, the mobile phones were in stand-by mode without own use. Measurements were taken close to the mobile phone (proximal), with a distance of $\sim 10 - 15$ cm between the PEM and mobile phone (for both studies), and distal from the source (exact location, see Figure 2), with a distance of ~ 50 cm for the public transport study and $\sim$70–80 cm for the car study. During data collection in the framework of the public transport study, the device distant to the source was carried in a waist pack in front of the body (Figure 2) in order to maintain a distance of ~ 50 cm from the emitting device.

The public transport study was carried out in four different settings: bus stop, train station, bus ride and train ride. Data collection took place during 3 weeks (from 25 January 2010 to 23 March 2010) in the morning and in the evening during regular commuting hours, always at the same time of the day and on the same travel routes. The scenarios were rotated each day to obtain for each scenario one morning and one evening measurement for each workday. The scenarios were rotated each day to obtain for each scenario one measurement for each workday. During the measurements, a prespecified activity diary was filled in to unequivocally attribute each measurement to the correct setting or area.

The car study consisted of five car rides, which were conducted on five different days between 13 November 2010 and 4 January 2011 on the same routes. In each ride, a distance of ~ 280 km had been covered. Rural, urban and highway areas were defined when leaving or entering the city or a highway, respectively, by-passing the road sign. By using GPS (Global Positioning System) recordings, measurements of each ride were classified as rural, urban or highway measurements.

All measurements of both studies had been collected by the same trained collaborator.

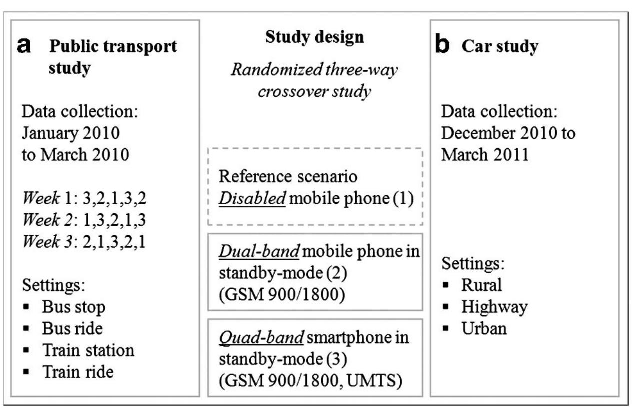

Figure 1. Overview of the study design consisting of the two sub-studies: public transport study (a) and the car study (b).

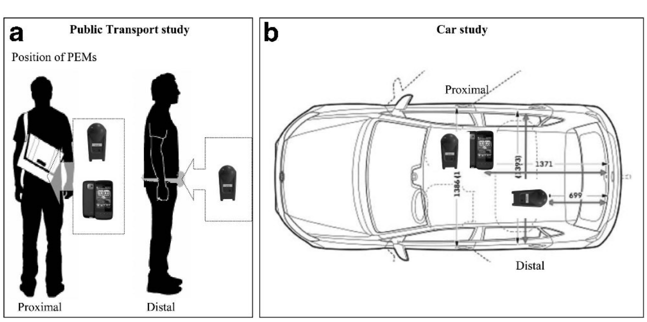

Figure 2. Overview of the placement of the mobile phone and the measurement devices in the public transport study (a) and the car study (b).

Personal Measurements

We used two PEMs of the type EME Spy 120 (SATIMO, Courtaboeuf, France, http://www.satimo.fr/), which were placed proximal and distal to the mobile phone. This portable device is capable of measuring 12 different frequency bands of RF-EMF, ranging from 88 MHz (frequency modulation) to 2500 MHz (W-LAN). Uplink and downlink mobile phone bands are measured separately. The measured frequency ranges for the uplink bands are 880–915 MHz (GSM900), 1710–1785 MHz (GSM1800) and 1920–1980 MHz (UMTS), which fits to the emission spectrum of the used mobile phones. Note that CDMA is not in use in the study country.

The measurement interval was set to 4 s in order to collect a large amount of data points.

Statistical Analysis

To take into account the measurements below the detection limit, arithmetic mean values, and other summary statistical measures were calculated using the robust regression on order statistics method[10] for each setting on each day separately. If less than three measurements were above the detection limit for a given setting and frequency band, the arithmetic mean value was set to 0.000265 mW/m^2.

RESULTS

A total of 109,668 measurements had been collected (64,551 measurements from the public transport study and 45,117 from the car study). The power flux density of the total uplink measurements of the three uplink bands combined (GSM900, GSM1800 and UMTS) was highly variable. For the reference scenario, highest uplink values were found during train rides (1.19 mW/m^2), whereas lowest values occurred during car rides in rural areas (0.0012 mW/m^2) (Figure 3a). Uplink levels during the reference scenario (mobile phone turned off) were higher in the public transport study than in the car study, and total uplink exposure mainly originates from GSM900 and GSM1800 frequency bands, although the contribution of UMTS is negligible (<0.001 mW/m^2, except for train rides: 0.0013 mW/m^2) (Figure 3a and 3b). Even during the quad-band scenario, the GSM bands were higher than the UMTS bands in all settings.

Public Transport Study

Total power flux density of all the measured frequency bands (88–2500 MHz) for all settings combined for the PEM placed proximal to the mobile phone was 0.65 mW/m^2 in the reference scenario, 0.43 mW/m^2 in the dual-band scenario and 0.73 mW/m^2 in the quad-band scenario. The average proportions of uplink measurements in all four transportation modes combined were 81.6% (reference), 72.6% (dual-band) and 55.3% (quad-band), respectively.

For all settings and scenarios combined, the percentage of nondetects for the device in vicinity to the source was 60.8% (67.7% for the distant device) for GSM900 and GSM1800 combined and 98.2% for UMTS.

During the scenarios with activated phones, GSM uplink (combination of GSM900 and GSM1800) measurements in public transports were not consistently higher compared with the reference scenario (Figure 3a and 3c), as would have been expected on the basis of our hypothesis. During train rides, where most of the location updates are expected to occur, measurement levels were actually lower with the activated phones. In contrast, UMTS uplink levels were always higher in the scenario with an activated quad-band phone compared with the two other scenarios without own UMTS emissions (Figure 3b). Except during

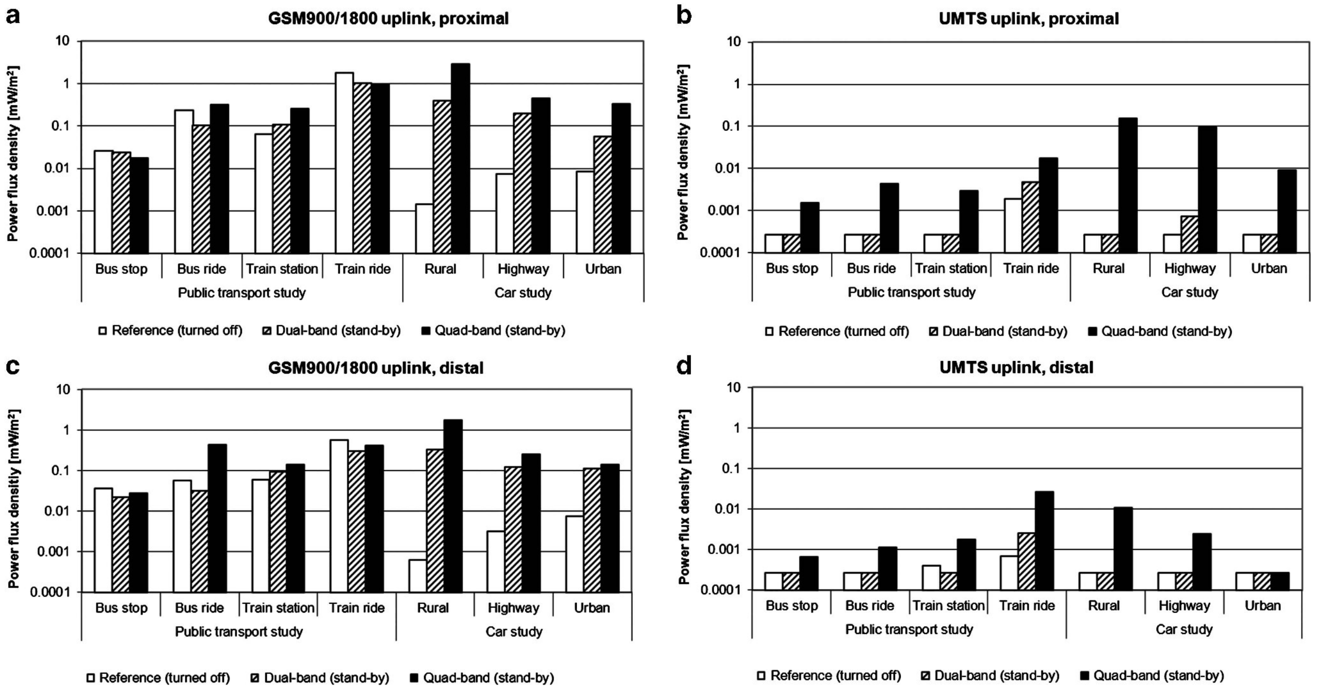

Figure 3. Arithmetic mean uplink power flux density levels (mW/m^2) in the public transport study and the car study subdivided in the GSM 900/1800 and UMTS frequency bands for the devices proximal (a, b) and distal (c, d) to the source (mobile phone).

train rides, this difference was smaller for the distal measurement device (Figure 3d). The data distribution for each scenario and frequency band is presented as Supplementary Figure 1a–d.

Car Study

Total power flux density of all measured frequency bands in all areas for the PEM placed proximal to the mobile phone was 0.12 mW/m^2 in the reference scenario, 0.35 mW/m^2 in the dual-band scenario and 1.62 mW/m^2 in the quad-band scenario. The proportions of uplink bands were 4.9%, 62% and 81.9%, respectively. For all settings and scenarios combined, the percentage of nondetects for the device in vicinity to the source was 88.4% (93.4% for the distant device) for GSM900 and GSM1800 combined and 99.2% for UMTS.

During the scenarios with activated phones GSM uplink measurements were considerably higher compared with the reference scenario (Figure 3a–d). For instance, in rural areas, GSM uplink of the proximal device was 0.0014 mW/m^2 for the reference scenario, 0.395 mW/m^2 for the dual-band scenario and 2.923 mW/m^2 for the quad-band scenario (Figure 3a). The proximal and distal devices showed similar values for GSM frequency bands.

With regard to UMTS uplink, levels were increased for the quad-band scenario compared with the two other scenarios (Figure 3b). This increase was more pronounced for the proximal device than for the distal device. For the distal device, it was even negligible for the urban areas (Figure 3d). The data distribution for each scenario and frequency band is presented as Supplementary Figure 1a–d.

DISCUSSION

Our study demonstrates that PEM measurements are affected by one's own mobile phone in stand-by mode. The effect was more pronounced in the car study than in the public transport study. This pattern is not surprising because measurements in one's own car are hardly affected by other people's mobile phone. During commuting in public transports, however, other people's mobile phones are influencing the uplink measurements considerably. Thus, GSM levels in the reference scenario during bus and train rides were about 100 times higher than those during car rides. As a consequence of this high background exposure in trains, due to the use of other people's mobile phone in a closed area intensified by the Faraday cage effect, the relative contribution of the location update from one's own mobile phone is small and the contribution of the own mobile phone is masked in our measurements.

This measurement study provided additional insights. First, UMTS uplink exposure is considerably lower than GSM uplink exposure. For UMTS, the impact of the own quad-band mobile phone (smart phones) was observable in almost all scenarios. However, the absolute contribution of UMTS signals to total uplink exposure (GSM900, GSM1800 and UMTS signals combined) was very small (0.2% for the public transport study and 5.4% for the car study). Second, for location updates, quad-band phones seem to use both the GSM and the UMTS frequency bands. We measured higher GSM than UMTS levels and found an indication that GSM location update of quad-band phones is more pronounced than GSM location update of dual-band phones. This suggests that quad-band phones execute more location updates than dual-band phones. Possibly, quad-band mobile phones need more frequent location updates because of new applications (apps) including push notifications. Push notifications, which require W-LAN or cellular connection, are a way for applications (newspaper, e-mail, messages and others) to provide alerts and information. Third, even for the distal PEM of the car study, we found considerable impact from one's own mobile phone. This implies that one's own mobile phone in a car is a relevant exposure source to the passenger(s) even if not carried on the body.

Our study implies that PEM uplink measurements are affected by one's own mobile phone in stand-by mode. This was best visible in the car study, where measurements were barely affected by other people's mobile phone. In public transports or when being stationary (in bus stop and train station), the relative impact of one's own phone was small compared with the other sources, and thus less clearly visible. Nevertheless, an impact on the measurement has to be expected, especially when moving. We also found some indications that RF-EMF contributions in stand-by mode will become more relevant in the future because of the increasing use of smart phones that need regular location updates. To the best of our knowledge, no study has yet investigated the exposure from location updates in real-life situations.

The study offers amendatory information about exposure provoked by other people. In this context, we observed higher RF-EMF exposure in settings in which a lot of people are present, as especially was perceived in public transports, particularly in trains, and in urban environments augmenting exposure levels. This was clearly shown by higher exposure levels for the reference scenario in which only background exposure levels were quantified.

Our results reflect a snapshot in time based on one type of mobile phone for each scenario and two mobile phone operators. Thus, it cannot be generalized to other countries or to the future, as the extent of location update is determined by various factors such as the type of phone and the implemented technology of the mobile phone network operators.[11] Thus, there is an urgent need to evaluate more thoroughly how personal RF-EMF exposure is affected by one's own phone in stand-by mode. A better knowledge of the relevance of this exposure source in comparison with RF-EMF exposure when talking on a phone helps clarify whether the duration of mobile phone use, the most common exposure surrogate in epidemiological RF-EMF research, is actually an adequate exposure proxy. In particular, when interested in whole-body exposure, new exposure assessment approaches have to be considered by taking into account the emission behaviour of mobile phones in stand-by mode. Whole-body exposure is of interest, for instance, in studies on leukaemia[12] or on the foetus during pregnancy.[13,14]

Our measurement study has some relevance for people who want to minimize their personal exposure. The study indicates that own uplink exposure during car driving can be considerably reduced (about a fraction of 100) when turning off one's own mobile phone in order to prevent it from location updates. Recently, the use of UMTS phones has been recommended as a precautionary measure, because UMTS calls are carried out with lower amount of radiation emissions.[15] Before this precautionary measure can be firmly given to the public, it has to be ensured that lower exposure during calls is not compensated with higher emissions in stand-by mode.

In summary, this study demonstrates the complexity of the RF-EMF emission pattern of mobile phones in stand-by mode. So far, this exposure source has been neglected in the RF-EMF research. More thorough studies are needed to quantify this contribution to the total personal exposure. Such knowledge is needed for the interpretation of previous RF-EMF research and for the design of future high-quality epidemiological research.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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15 Baumann J, Landstorfer FM, Geisbusch L, Georg R. Evaluation of radiation exposure by UMTS mobile phones. *Electron Lett* 2006; **42**(4): 225–226.

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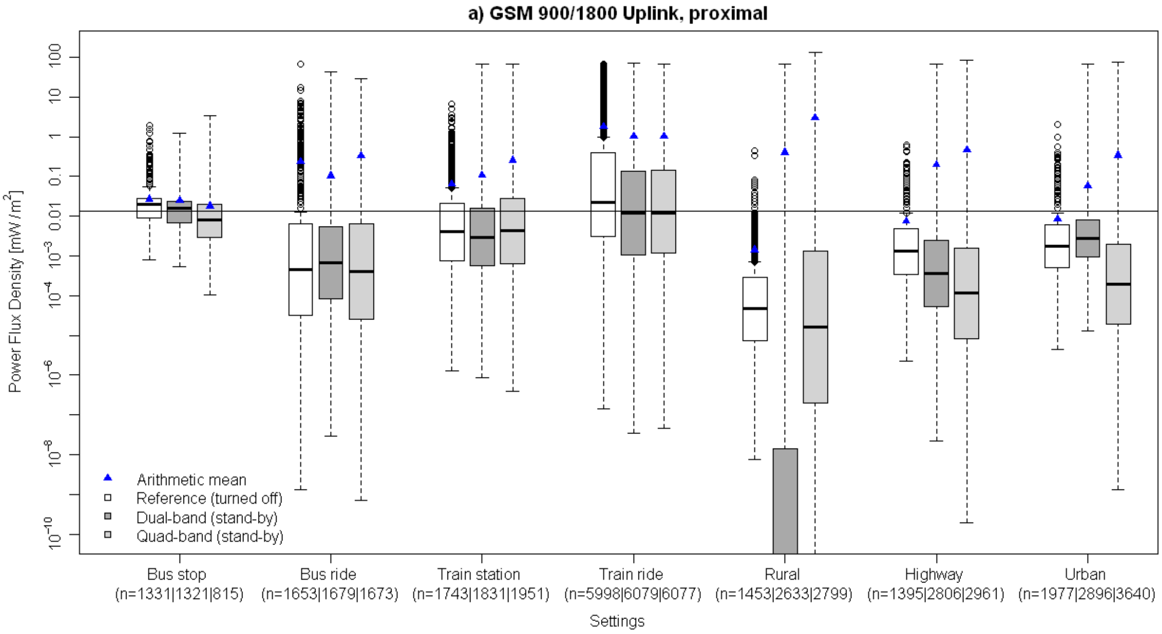
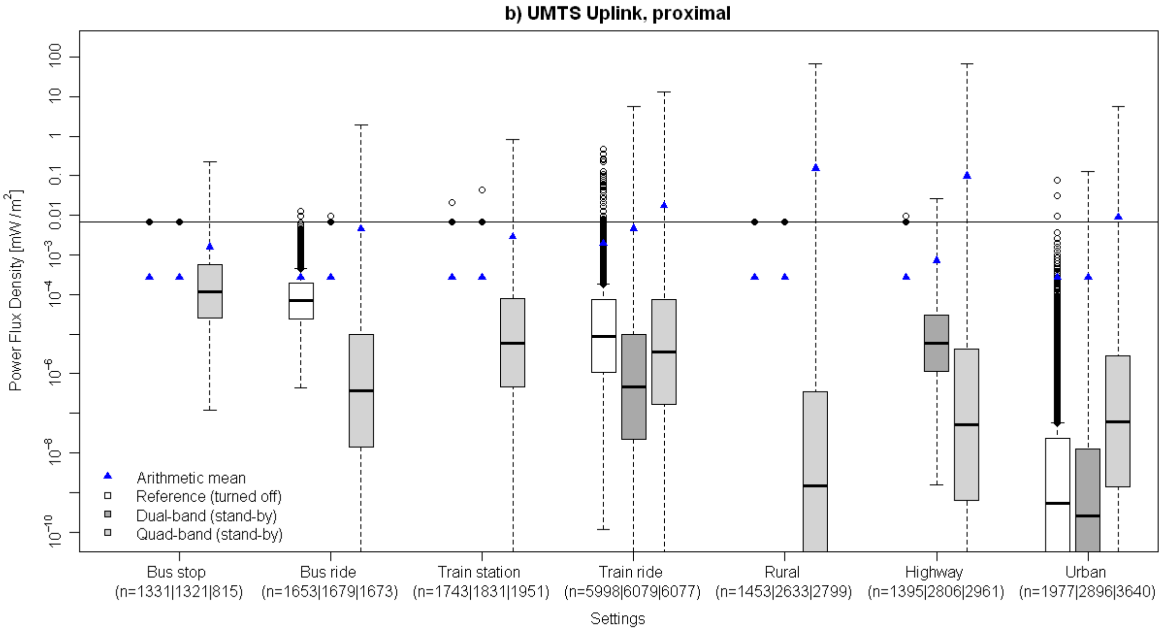
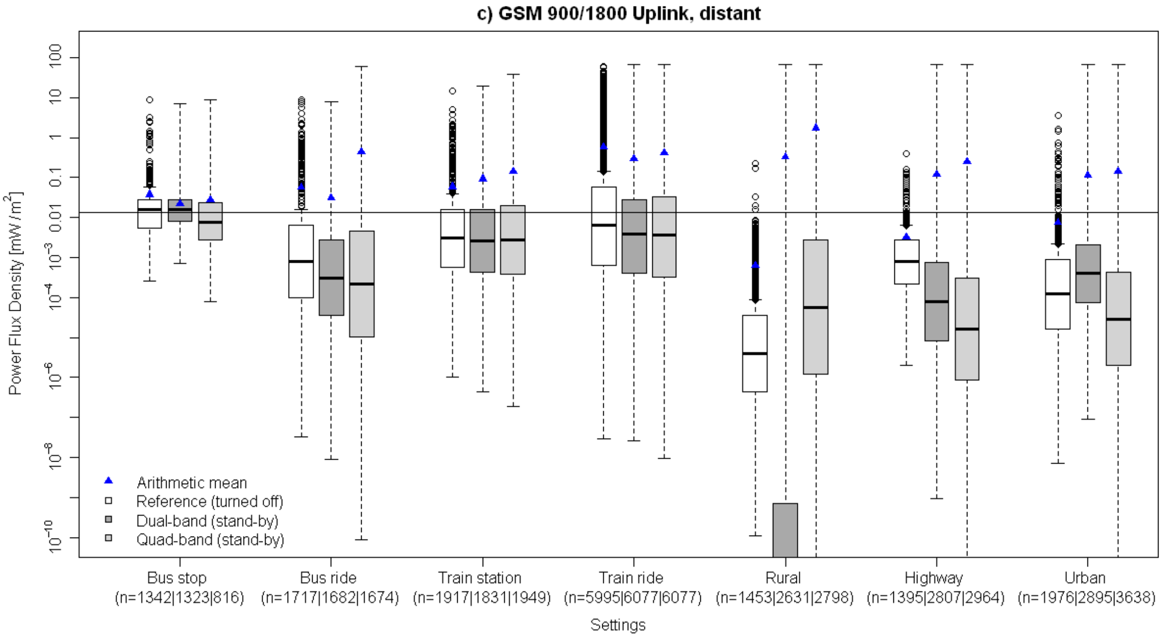
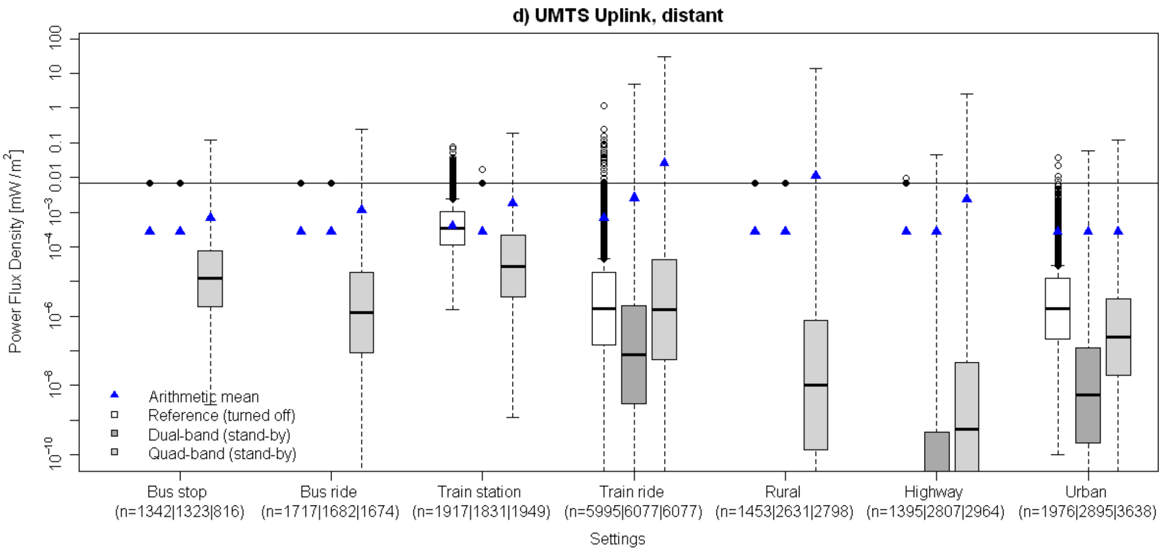
SUPPLEMENTARY MATERIAL

FIGURE 1.






c) GSM 900/1800 Uplink, distant
Power Flux Density [mW / m^2]
100
10
1
0.1
0.01
10^{-3}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
Arithmetic mean
Reference (turned off)
Dual-band (stand-by)
Quad-band (stand-by)
Bus stop (n=1342|1323|816)
Bus ride (n=1717|1682|1674)
Train station (n=1917|1831|1949)
Train ride (n=5995|6077|6077)
Rural (n=1453|2631|2798)
Highway (n=1395|2807|2964)
Urban (n=1976|2895|3638)
Settings


d) UMTS Uplink, distant
Power Flux Density [mW / m^2]
100
10
1
0.1
0.01
10^{-3}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
Arithmetic mean
Reference (turned off)
Dual-band (stand-by)
Quad-band (stand-by)
Bus stop (n=1342|1323|816)
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Highway (n=1395|2807|2964)
Urban (n=1976|2895|3638)
Settings

5 Reproducibility of personal RF-EMF measurements

Article 2: Use of portable exposure meters for comparing mobile phone base station radiation in different types of areas in the cities of Basel and Amsterdam

Damiano Urbinello[1,2], Anke Huss[3], Johan Beekhuizen[3], Roel Vermeulen[3] and Martin Röösli[1,2]

[1] Swiss Tropical and Public Health Institute

[2] University of Basel, Switzerland

[3] Institute for Risk Assessment Sciences, Utrecht University, The Netherlands

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Use of portable exposure meters for comparing mobile phone base station radiation in different types of areas in the cities of Basel and Amsterdam

Damiano Urbinello [a,b], Anke Huss [c], Johan Beekhuizen [c], Roel Vermeulen [c], Martin Röösli [a,b,*]

[a] Swiss Tropical and Public Health Institute, Department of Epidemiology and Public Health, Socinstrasse 57, Basel, CH-4002, Switzerland
[b] University of Basel, Petersplatz 1, Basel, CH-4003, Switzerland
[c] Institute for Risk Assessment Sciences, Department of Environmental Epidemiology, Utrecht University, Yalelaan 2, Utrecht NL-3508 TD, the Netherlands

HIGHLIGHTS

- High reproducibility of mobile phone base station exposure levels
- Portable devices are suitable for monitoring trends in the everyday environment.
- Base station radiation exposure is the dominant exposure source outdoors.
- High spatial and low temporal variability of mobile phone base station exposure
- Exposure levels of total RF-EMF exposure were highest in downtown and business areas.

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ABSTRACT

Background: Radiofrequency electromagnetic fields (RF-EMF) are highly variable and differ considerably within as well as between areas. Exposure assessment studies characterizing spatial and temporal variation are limited so far. Our objective was to evaluate sources of data variability and the repeatability of daily measurements using portable exposure meters (PEMs).
Methods: Data were collected at 12 days between November 2010 and January 2011 with PEMs in four different types of urban areas in the cities of Basel (BSL) and Amsterdam (AMS).
Results: Exposure from mobile phone base stations ranged from 0.30 to 0.53 V/m in downtown and business areas and in residential areas from 0.09 to 0.41 V/m. Analysis of variance (ANOVA) demonstrated that measurements from various days were highly reproducible (measurement duration of approximately 30 min) with only 0.6% of the variance of all measurements from mobile phone base station radiation being explained by the measurement day and only 0.2% by the measurement time (morning, noon, afternoon), whereas type of area (30%) and city (50%) explained most of the data variability.
Conclusions: We conclude that mobile monitoring of exposure from mobile phone base station radiation with PEMs is useful due to the high repeatability of mobile phone base station exposure levels, despite the high spatial variation.

1. Introduction

The substantial increase and development of new telecommunication technologies in the last two decades resulted in a fundamental change of radiofrequency electromagnetic fields (RF-EMF) exposure patterns in the everyday environment (Frei et al., 2009b; Neubauer et al., 2007; Röösli et al., 2010). The Research Agenda of the World Health Organization (WHO) considered the quantification of personal RF-EMF exposure and identification of the determinants of exposure in the general population as a high priority research need (World Health Organization, 2010). However, exposure quantification is complex due to the high variability of RF-EMF levels in the environment (Bornkessel et al., 2007; Frei et al., 2009a; Joseph et al., 2008; Röösli et al., 2010).

There are different strategies and methodologies to monitor RF-EMF exposure. In general, two types of measurement procedures have been developed, fixed-location and mobile monitoring. Fixed-location

* Corresponding author at: Swiss Tropical and Public Health Institute, Department of Epidemiology and Public Health, University of Basel, Socinstrasse 57, Basel CH-4002, Switzerland. Tel.: +41 61 284 83 83; Fax: +41 61 284 85 01.
E-mail addresses: Damiano.Urbinello@unibas.ch (D. Urbinello), A.Huss@uu.nl (A. Huss), J.Beekhuizen@uu.nl (J. Beekhuizen), R.C.H.Vermeulen@uu.nl (R. Vermeulen), Martin.Roosli@unibas.ch (M. Röösli).

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measurements with a spectrum analyzer are very accurate for determination of exposure at a specific point in time and space. However, this type of exposure assessment method is time and resource intensive in terms of equipment, costs and trained personnel (Bornkessel et al., 2010; Joseph et al., 2009). As a consequence, collecting data representing typical exposure levels over time in a wide geographic area is challenging if not impossible (Bornkessel et al., 2010). In contrast, portable exposure meters (PEMs) allow collecting numerous measurements with relative little effort at different locations (Röösli et al., 2010). Such devices have been successfully applied in a few previous studies (Bolte and Eikelboom, 2012; Frei et al., 2009b; Joseph et al., 2010; Thuróczy et al., 2008; Usher, 2010; Viel et al., 2009).

Due to high spatial variation of RF-EMF around base stations (Bornkessel et al., 2007), exposure varies considerably within as well as between areas, resulting in complex exposure patterns and it is largely unknown how reproducible personal measurements are in a given area. Such information is, however, urgently needed when planning exposure monitoring in order to determine adequate sampling rates and possibly repeated measurements to obtain data that are representative of the true exposure.

In our analysis, we studied the spatial and temporal variability in RF-EMF exposure levels in different types of areas with concurrently conducted personal measurements in the cities of Basel and Amsterdam. We used repeated measurements in both cities to examine how repeatable measurements with PEMs are according to type of area, and to evaluate the suitability of PEM measurements for monitoring purposes.

2. Materials and methods

2.1. Study design

Data collection took place at the same dates and the same times of the day in Basel and Amsterdam between November 10^{th}, 2010 and January 27^{th}, 2011. Measurements in each area were taken every second week at two consecutive days on Wednesdays and Thursdays, respectively. On each measurement day, the timing of the area measurement sequence was shifted. This rotation scheme ensured having measurements in the morning, during noontime and in the afternoon for each area.

We selected typical areas in both cities, yet different types of urban areas (Table 1): business, downtown and residential areas. A measurement path of about 2 km length (Table 1) was chosen (online Figs. 1 and 2) per area. We included a downtown area with a busy pedestrian zone. The business area contains business venues with large building complexes. The central residential areas are located in zones with higher buildings (4 to 5 floors) and more traffic as well as more people on the sidewalks. Typical non-central residential areas in Basel are located outside the city center in quiet residential zones with building heights of about 2 to 3 floors and relatively large proportions of green space. In Amsterdam, one of the two non-central residential areas is situated partly in a quiet area (Sloterplas), whereas the second area is considered as a high-rise residential area with higher buildings (6 to 7 floors).

2.2. Measurements

For data collection in the city of Basel, we used a PEM of the type EME Spy 120 (SATIMO, Courtaboeuf, France, http://www.satimo.fr/) and in Amsterdam, a PEM of the type EME Spy 140. The portable device EME Spy 120 is capable of measuring 12 different frequency bands of RF-EMF, ranging from FM (Frequency Modulation, 88–108 MHz) to W-LAN (Wireless Local Area Network, 2400–2500 MHz). Its lower and upper sensitivity range is 0.0067 and 66.3 mW/m^2 (electric field strength between 0.05 and 5 V/m) respectively. The exposimeter EME Spy 140 measures 14 frequency bands of RF-EMF, ranging from FM to W-LAN 5G (5150–5850 MHz). This device has a higher sensitivity range at the lower detection limit of 0.000067 to 66.3 mW/m^2 (electrical field strength between 0.005 and 5 V/m). The interval between two measurements was set to 4 s, which corresponds to a distance of about 4.4 m, assuming a walking speed of approximately 4 km/h. Before September 2010 and after April 2011, accuracy checks of the devices were performed at the Swiss Federal Institute of Technology in Zurich (ETH). The results of the tests showed that accuracy of the devices did not change during the whole data collection period. However, we found indications that cross-talk occurred between DECT (Digital Enhanced Cordless Telecommunications) and GSM1800 (Global System for Mobile Communications) downlink signals for both, the EME Spy 120 as well as the EME Spy 140. Thus, we did not consider DECT when calculating total RF-EMF exposure levels.

For the measurements in Basel, the exposimeter was placed in a pushchair cart with a distance of about 1 m to the assistant performing the measurements and at around 1 m height above ground. The same was applied in Amsterdam, except that a bicycle cart was used and the assistant was walking beside, pushing the bicycle, ensuring about same walking speed in both cities. In both cities, the mobile phone of the assistant taking the measurements was turned off during measurements.

Table 1
Overview of the selected areas.

Denotation	Basel: area name/measurement path length/density of base stations*	Amsterdam: area name/measurement path length/density of base stations*	Area characteristics
Non-central residential area 1	Im Langen Loh 2.3 km >10 base stations	Sloterplas 2.2 km <5 base stations	Building height: 2 to 3 floors Near a quiet area and along a busy street (only Amsterdam)
Non-central residential area 2	Byfangweg 2 km >10 base stations	Plesmanlaan 1.9 km 5–10 base stations	Building height: 3 to 4 floors and quiet area (Basel) High-rise residential area with buildings up to 6–7 floors (Amsterdam)
Central residential area	Gundeldingen 2.3 km >10 base stations	Albert Cuypstraat 1.7 km >10 base stations	Building height: 4 to 5 floors Shops Residential Lot of activity in terms of pedestrian
Downtown	Barfüsserplatz/Marktplatz 2.1 km >10 base stations	Leidseplein 2 km >10 base stations	Meeting point Pedestrian area with strolling people Traffic and many trams
Business area	Messeplatz 2.2 km > 10 base stations	Zuidas 2 km > 10 base stations	Conference venue/business place Large building complex

Base station density in three categories: <5 base stations; 5–10 base stations; >10 base stations. Within a buffer of 500 m along the measurement path.

Table 2
Overview of average exposure as well as the percentage of values above the threshold of 0.5 V/m and 1 V/m, respectively, for all frequency bands combined.

Exposure from all frequency bands combined[a]			Arithmetic mean values	Percentage of values over threshold	
			[V/m]	0.5 V/m	1 V/m
		n	Total	Total	Total
All areas	*BSL*	20,063	0.26	4.92%	0.57%
	AMS	28,183	0.47	30.97%	2.64%
Non-central residential area 1	*BSL*	4302	0.09	0.05%	0.02%
	AMS	6110	0.43	19.26%	3.22%
Non-central residential area 2	*BSL*	3625	0.27	6.68%	1.74%
	AMS	5575	0.35	10.80%	0.27%
Central residential area	*BSL*	4608	0.19	2.13%	0.13%
	AMS	4817	0.35	12.21%	1.41%
Downtown	*BSL*	3866	0.32	7.89%	0.83%
	AMS	6030	0.55	43.20%	3.98%
Business area	*BSL*	3662	0.32	9.31%	0.33%
	AMS	5651	0.63	66.45%	3.96%

[a] Sum of all mobile phone uplink and downlink frequency bands, FM, TV3, TETRAPOL, TV4/5 and W-LAN.

2.3. Statistical analysis and data management

Arithmetic mean values for each frequency band in each area at each day were separately calculated using the robust regression on order statistics (ROS) method (Röösli et al., 2008), since a large proportion of PEM measurements were censored (below the lower detection limit of the PEM). In order to have comparable results for Amsterdam and Basel, due to the use of two types of PEMs with different lower detection limits (EME Spy 120: 0.05 V/m; EME Spy 140: 0.005 V/m), we also censored Amsterdam data at 0.05 V/m to calculate mean values using ROS. In addition, the proportion of measurements above the thresholds of 0.5 and 1 V/m was determined to compare the distribution of peak exposure levels. All calculations were conducted using power flux density values and then back-transformed to electric field strengths (V/m), except for analysis of variance (ANOVA) calculations.

We focused on mobile phone base station downlink exposure, i.e. the sum of GSM900 (925–960 MHz), GSM1800 (1805–1880 MHz) and UMTS (Universal Mobile Telecommunications System, 2110–2170 MHz), as well as mobile phone uplink (handset) exposure: i.e. the sum of GSM900 (880–915 MHz), GSM1800 (1710–1785 MHz) and UMTS (1920–1980 MHz). In this paper, total exposure is defined as the sum of all mobile phone uplink and downlink frequency bands as well as FM (88–108 MHz), TV3 (Television, 174–223 MHz), TETRAPOL (professional radio communication standard, 380–400 MHz), TV4/5 (470–830 MHz) and W-LAN (2400–2500 MHz). To evaluate sources of data variability, ANOVA calculations were conducted based on daily means of power flux density levels for all frequencies combined (total), as well as separately for downlink and uplink signals. For the ANOVA, explanatory variables were measurement day, time of the day (3 categories: 09:15–11:59; 12:00–12:59 and 13:00–16:50), type of area (central and non-central residential, downtown and business areas) and city (Basel vs. Amsterdam).

Summary statistics were calculated using R version 2.11.1. ANOVA was calculated using STATA version 10.1 (StataCorp, College Station, TX, USA) based on a balanced data set of arithmetic mean values.

Some technical failures occurred during data collection period (Amsterdam: failure of the device on the second measurement day (11th November 2011); missing GPS data for the 1st and 2nd measurement day (10th and 11th November 2010); Basel: uplink values were excluded for the 11th November (non-central residential area 2 and business area) and 23rd December 2010 (central residential and downtown area) and thus for calculation of total RF-EMF exposure, uplink values for these days were excluded).

3. Results

3.1. Comparison of mean RF-EMF exposure levels between areas

In total, 20,063 downlink and 18,700 uplink measurements were collected in all Basel areas and 28,183 uplink and downlink measurements in Amsterdam areas. Area-specific averages of exposure from all frequency bands combined (total RF-EMF) ranged from 0.09 V/m (non-central residential area in Basel) to 0.63 V/m (business area in Amsterdam) (Table 2). The highest total RF-EMF exposure levels occurred in the downtown and business areas (Table 2). Whereas the lowest values were observed in non-central residential areas.

Similarly, exposure to mobile phone base stations (all downlink frequencies combined: sum of GSM900, GSM1800 and UMTS) was highest in the downtown and business areas and lowest in non-central residential areas (Table 3). In all areas, the GSM900 and GSM1800 bands were the main contributors to total downlink exposure.

Regarding peak values, a similar pattern was found as for average exposure values, with more peak values above 0.5 V/m or 1 V/m in the downtown and business area for total (all frequency bands combined) and downlink exposure levels (Table 3). Overall, measurements above 1 V/m were rare in all three downlink bands in all areas.

Exposure from mobile phone handsets (uplink) was considerably lower than downlink values in all areas. Peak values were rare and in Basel for all areas combined, the proportion of uplink measurements above 0.5 V/m was 0.05% for GSM900 and 0.12% for GSM1800. For Amsterdam, the respective proportions were 0.11% and 0.14%. In

Table 3
Overview of average exposure as well as the percentage of values above the threshold of 0.5 V/m and 1 V/m, respectively for mobile phone downlink frequency signals.

Mobile phone base station exposure		Arithmetic mean values [V/m]					Percentage of values over threshold					
							0.5 V/m			1 V/m		
		n	GSM 900	GSM 1800	UMTS	Total DL[a]	GSM 900	GSM 1800	UMTS	GSM 900	GSM 1800	UMTS
All areas	*BSL*	20,063	0.13	0.19	0.08	0.24	4.61%	2.45%	0.07%	0.40%	0.36%	None
	AMS	28,183	0.27	0.30	0.14	0.43	5.66%	10.18%	0.38%	0.37%	0.77%	0.11%
Non-central residential area 1	*BSL*	4302	0.02[b]	0.05	0.07	0.09	None	None	None	None	None	None
	AMS	6110	0.23	0.34	0.03[b]	0.41	4.06%	10.74%	None	0.15%	2.16%	None
Non-centralresidential area 2	*BSL*	3625	0.05	0.26	0.04[b]	0.26	0.06%	5.68%	None	None	1.49%	None
	AMS	5575	0.28	0.10	0.16	0.34	5.88%	None	0.34%	0.13%	None	0.02%
Central residential area	*BSL*	4608	0.09	0.12	0.09	0.18	0.74%	0.33%	None	0.04%	None	None
	AMS	4817	0.18	0.24	0.12	0.33	3.11%	4.19%	0.15%	0.42%	None	0.02%
Downtown	*BSL*	3866	0.16	0.24	0.10	0.30	1.27%	2.61%	None	0.21%	0.36%	None
	AMS	6030	0.33	0.38	0.17	0.53	8.57%	17.73%	0.48%	1.01%	1.06%	0.02%
Business area	*BSL*	3662	0.21	0.18	0.10	0.30	3.60%	1.12%	0.19%	0.22%	None	None
	AMS	5651	0.29	0.37	0.16	0.49	5.77%	16.69%	0.90%	0.12%	0.39%	None

[a] Downlink (exposure from mobile phone base stations).
[b] Below the sensitivity level of the exposimeter. Results are tenuous.

the UMTS band, no uplink measurements above 0.05 V/m occurred in Basel or in Amsterdam.

3.2. Analysis of data variability between areas

Exposure levels within areas had high spatial variability, Fig. 1 demonstrates, however, that exposure levels were similar on various measurement days and times of the day at the same location on the measurement path. Thus, repeated measurements showed a high reproducibility for mobile phone base station exposure (all downlink frequencies combined):

Fig. 2 shows that average downlink exposure levels per area remained fairly constant during the measurement period between November 2010 and January 2011. This is confirmed by variance analyses (Table 4). Day of measurement as well as time of the day explained only a very small proportion of the mobile phone base station data variance (0.6% and 0.2%). Most of the observed data variance is explained by city (50%) and area (30%). Similar results were found for total RF-EMF exposure. For mobile phone handset exposure, day of measurement (3.5%) and time of the day (1.5%) explained somewhat more data variability.

4. Discussion

This study analyzed the sources of data variability and quantified RF-EMF exposure levels in four different types of urban environments of two European cities based on repeated measurements with portable exposimeters following a standardized measurement protocol. We found that total (all frequency bands combined) mean exposure levels and exposure from mobile phone base stations were higher in downtown and business areas compared to residential areas. Exposure was highly spatially variable and varied considerably between the areas.

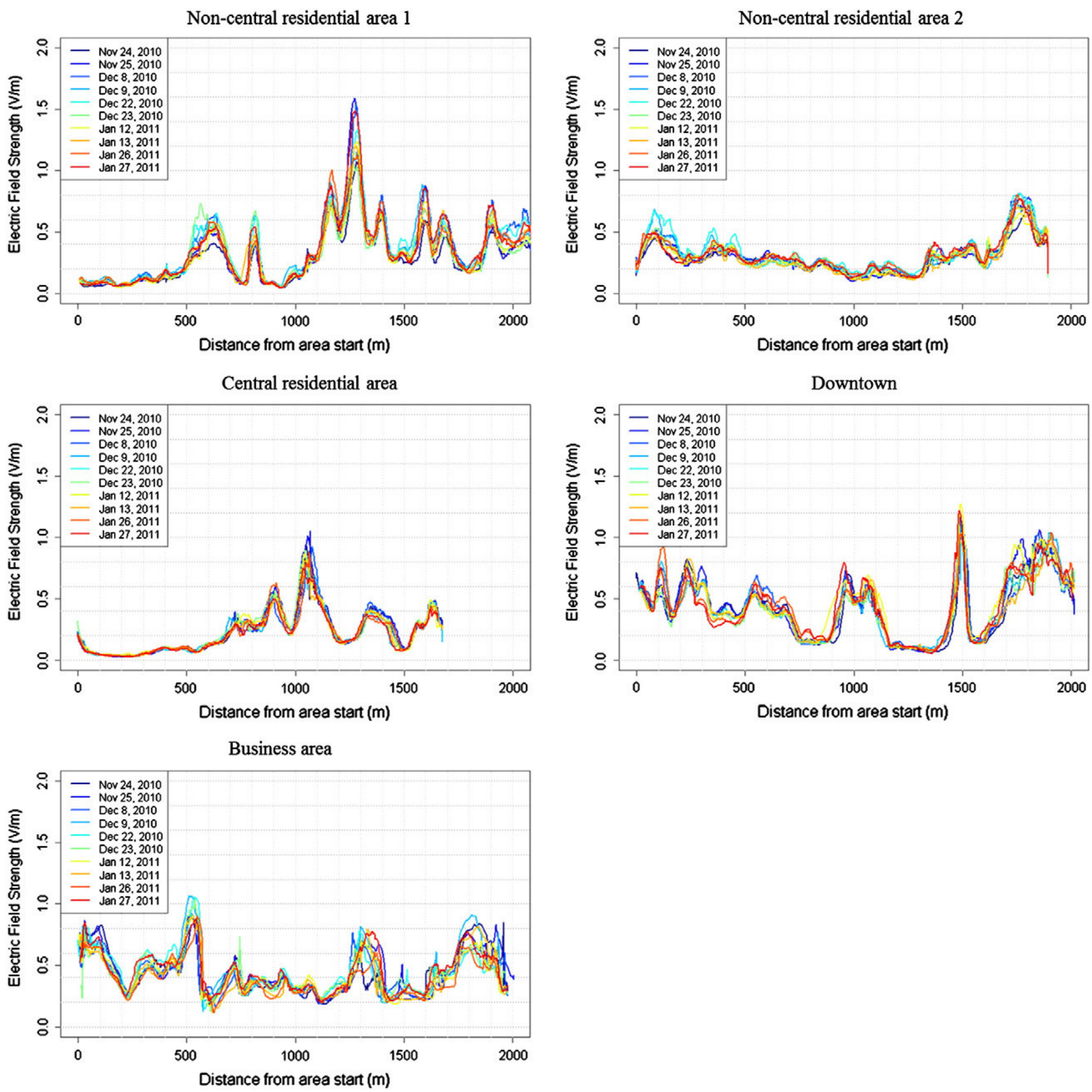

Fig. 1. Repeatability of mobile phone base station measurements (downlink) of one EME Spy 140 PEM for each area in Amsterdam: the graphs show the moving average of the electric field strengths along the whole measurement paths on 10 measurement days (no data for the 1st and 2nd measurement day, 10th and 11th November 2010). Moving averages were taken over 11 successive measurements, corresponding to a measurement interval of 44 s.

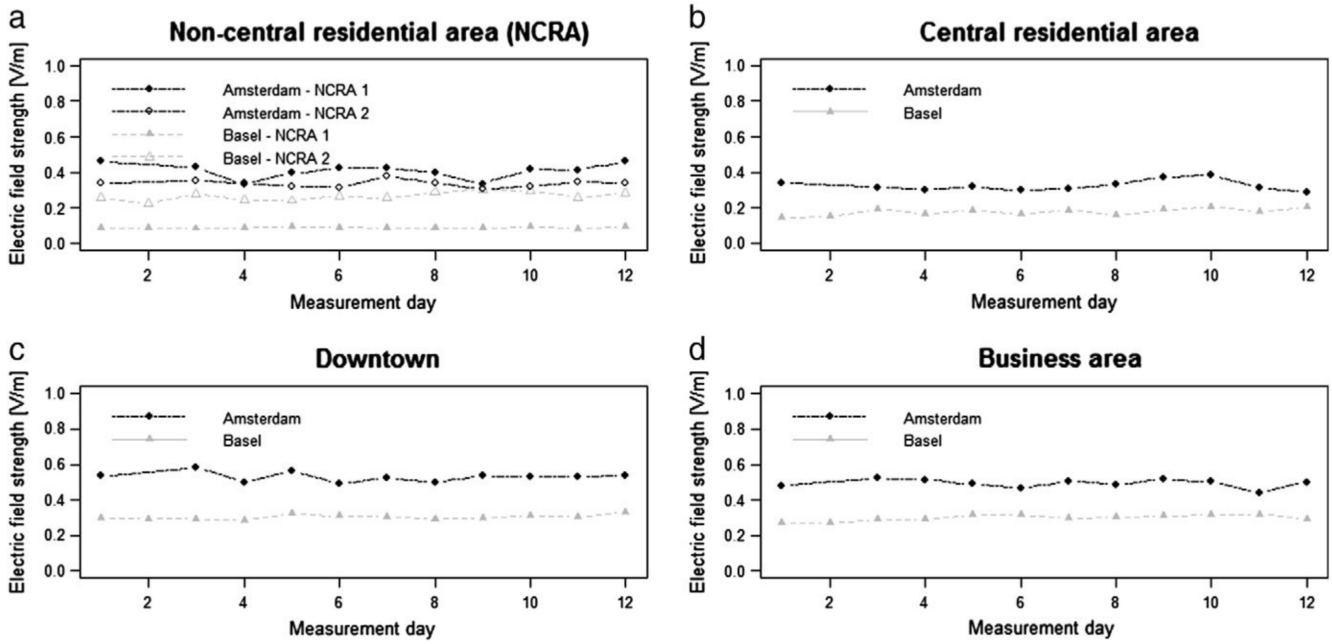

Fig. 2. Average mobile phone base station exposure (downlink) per measurement day according to type of area (no data for the 2^{nd} measurement day in Amsterdam).

However, temporal variability was low and we found good repeatability of measurements in the same area when conducting the measurements at different dates and different times of the day.

4.1. Comparison of exposure levels with other studies

RF-EMF exposure levels in our study were in accordance with studies of Joseph et al. (2008), who found downlink levels from GSM900 and GSM1800 in Gent and Brussels of up to 0.52 V/m in outdoor areas as well as with Frei et al. (2009a,b) with an average of total exposure of 0.28 V/m performed in Basel outdoors. The contribution of mobile phone base station signals to total RF-EMF exposure was about 89% in Basel and 81% in Amsterdam, whereas uplink exposure was low (Basel: 6% and Amsterdam: 4%). However, outdoor measurements of uplink exposure depend on time, weather conditions and place. An additional explanation might be that uplink exposure levels were somewhat underestimated since when walking with a bicycle or a push-chair cart, people keep in general more distance to a person as without. A small increase in distance will considerably reduce the amount of uplink exposure. During rush hour, lunch hour as well as in places where people cumulate, such as at sidewalks of pubs, in shopping areas and the city center, exposure from mobile phone handsets was found to be higher compared to other areas (e.g. residential areas). Other studies have also reported mobile phone base station radiation exposure to be the dominant exposure source when being outdoors: Frei et al. (2009b) observed that in a Swiss population sample with personal measurements collected between 2007 and 2008, mobile phone base station signals accounted for about 52.6% of outdoor exposure levels. The proportion may be somewhat lower compared to our study, because in population survey studies, participants do not have to turn off their own mobile phone as in our study. A European comparison of personal RF-EMF exposure in urban areas is in line with our findings that exposure from mobile phone base stations in outdoor urban environments was important and dominating, particularly in measurement series performed in Belgium (around 90%) and in the Netherlands (approximately 80%) (Joseph et al., 2010). In these two countries, also the own mobile phone was switched off when collecting the measurements.

Within the mobile phone base station bands, UMTS exposure was considerably lower than GSM900 and GSM1800 exposure (Basel: 12%; Amsterdam: 10%). These results are in line with a study of Bornkessel et al. (2007) in Germany showing that for 85% of all measurement points, exposure in both GSM bands was higher than UMTS exposure. In a Swiss study conducted in public transports and cars, results suggested that UMTS uplink exposure was considerably lower than GSM uplink exposure (Urbinello and Röösli, 2013).

Regarding base station densities in both cities, GSM base stations are in the majority (online Figs. 1 and 2). However, with mobile phones using web-based applications, especially since the introduction of smartphones, UMTS (3^{rd} Generation) as well as newer technologies have increased over the last years and will likely become more important in the future.

Table 4
Analysis of variance of daily mean exposure levels expressed as power flux density for total RF-EMF, downlink and uplink frequency bands.

Source	d.f.	Explained variance[a]	F	p
Total				
Measurement day	11	0.30	0.15	0.10
Time of the day[b]	2	0.18	0.51	0.60
City	1	44.84	247.92	<0.001
Area	4	32.93	45.52	<0.001
Whole model	18	83.54	25.66	<0.001
Downlink				
Measurement day	11	0.59	0.33	0.98
Time of the day[b]	2	0.20	0.61	0.55
City	1	47.37	292.5	<0.001
Area	4	31.31	48.34	<0.001
Whole model	18	85.26	29.25	<0.001
Uplink				
Measurement day	11	3.62	0.9	0.54
Time of the day[b]	2	1.51	2.06	0.13
City	1	39.41	107.63	<0.001
Area	4	15.88	10.84	<0.001
Whole model	18	67.41	10.23	<0.001

[a] Percentage of total variance.
[b] 3 categories: 09:15–11:59; 12:00–12:59 and 13:00–16:50.

4.2. Interpretation

One important finding of our study is the high repeatability of mobile phone base station exposure measurements on the same route, although spatial variability of RF-EMF is high. We found high repeatability for area averages based on a measurement duration of approximately 30 min which corresponds to 450 data points. High repeatability was also observed for measurements at a given location on the path when relying on moving averages of 11 data points. Our ANOVA indicates that time of the day and date have little impact on recordings. Since we only measured during daytime at two work-days (Wednesday and Thursday), between November and January, we cannot exclude that differences between work-days, weekends, holidays and seasons, as well as between daytime and evening measurements could be larger. In a personal RF-EMF measurement study conducted by Bolte and Eikelboom (2012) total mean exposure during evening (0.382 mW/m^2) was about twice the exposure than during daytime (0.183 mW/m^2) and about four times the exposure during night (0.095 mW/m^2). But at least partly, this difference is likely to be explained by different types of activities of the participants at different time of the day. We have not conducted measurements during the weekend and thus were not able to estimate data variability between work-days and weekend. However, Frei et al. (2009b) and Viel et al. (2011) found similar exposure values for weekend and work-days suggesting that this factor is not very relevant. Interestingly, high repeatability of measurements on the same route could also be confirmed when expanding the study period to 10 months (Beekhuizen et al., 2013). We also found little indications that repeatability depends on the data variability or the proportion of measurements above certain thresholds, since the pattern of the repeated measurements was similar in all four types of areas.

4.3. Strengths and limitations

To our knowledge, this is the first study that used a standardized measurement protocol with concurrently conducted data repeated measurement series from different types of urban areas to systematically evaluate repeatability of personal RF-EMF measurements. A further strength of the study was that PEMs were placed distant to the body in order to avoid shielding of the measurements by the own body, which has been demonstrated to result in an underestimation of the exposure (Iskra et al., 2010). Since, during measurements, the own mobile phone was turned off, our uplink values can be attributed to other peoples' mobile phone, which was not the case in previous personal exposure studies based on volunteers (Frei et al., 2009b; Viel et al., 2009), which is a limitation for source attribution (Urbinello and Röösli, 2013).

Our study also has limitations; the PEMs used in both cities were not of the same type and differed in their lower detection limit. However, we censored the Dutch data at the same detection limit as the Swiss data (0.05 V/m) to obtain comparable results and we excluded the two additional frequency bands for calculations of total RF-EMF exposure (i.e. WiMax (Worldwide Interoperability for Microwave Access): 3400 to 3800 MHz and W-LAN 5G: 5150 to 5850 MHz) measured by the EME Spy 140 used for data collection in Amsterdam. We also checked whether the summary statistics of the Dutch data differed depending on censoring at the detection limit of the EME Spy 120 or EME Spy 140 device, but found that not to be the case (data not shown). Uncertainty of the measurement accuracy of such portable devices has been investigated before (Bolte et al., 2011; Bornkessel et al., 2010; Lauer et al., 2012).

Ideally, one would be able to choose measurement paths that are representative of the exposure a population would have in the respective area, but it is unclear how this could be achieved. The selection of the areas and measurement paths through the different areas of the city determines to a large extent our RF-EMF measurement levels. The extent of this impact is difficult to quantify and thus the observed higher exposure levels in Amsterdam have to be interpreted with caution in terms of the general exposure situation in both cities. More comprehensive data collection is needed to compare exposure situation across cities and countries.

4.4. Conclusions

Our study indicates that RF-EMF measurements with PEMs allow collecting large amount of data in a short time period, resulting in robust data to characterize mean exposure levels in an urban area based on measurements collected within 30 min. Our repeated measurement series show little temporal variation in exposure levels, minimizing the need for many repeated measurements. Thus, exposure surveys using PEMs may be suitable to monitor RF-EMF exposure in the everyday environment.

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.scitotenv.2013.09.012.

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ONLINE FIGURES

FIGURE 1. Base station density and measurement paths in the different areas of the city of Basel.

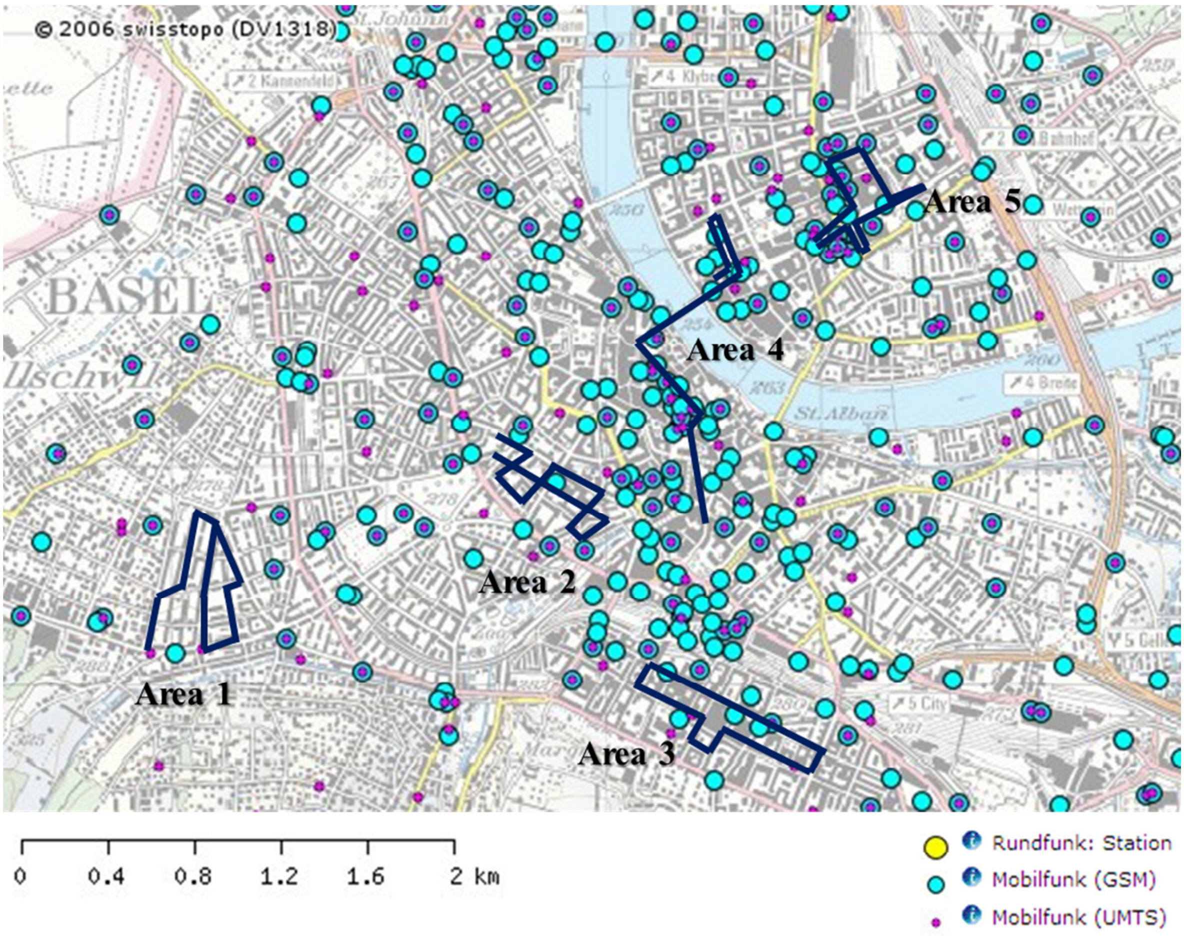
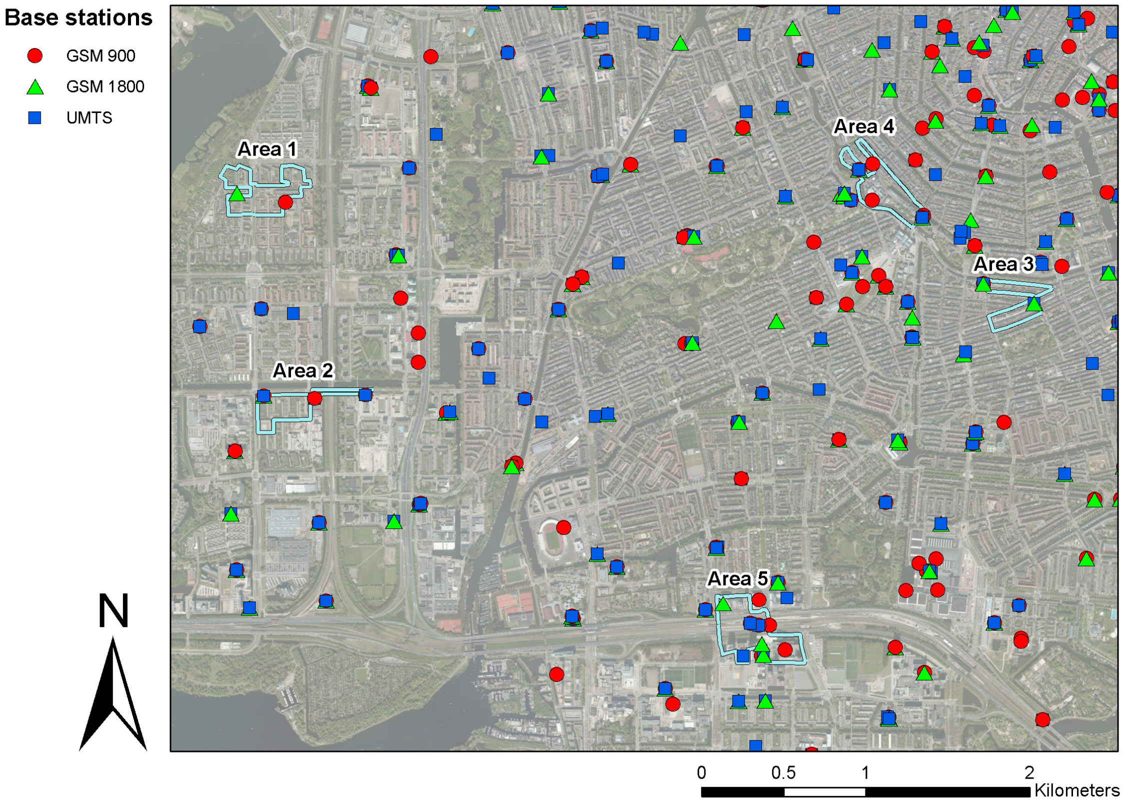


FIGURE 2. Base station density and measurement paths in the different areas of the city of Amsterdam.



6 Influence of the mobile phone base station network on the exposure situation of the population

Article 3: Radio-frequency electromagnetic field (RF-EMF) exposure levels in relation to regulatory limits in different outdoor urban environments across several European cities

Damiano Urbinello[1,2,3], Wout Joseph[3], Anke Huss[4], Leen Verloock[3], Johan Beekhuizen[4], Roel Vermeulen[4], Luc Martens[3] and Martin Röösli[1,2]

[1] Swiss Tropical and Public Health Institute
[2] University of Basel, Switzerland
[3] Department of Information Technology, Ghent University / iMinds
[4] Institute for Risk Assessment Sciences, Utrecht University, The Netherlands

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Radio-frequency electromagnetic field (RF-EMF) exposure levels in different European outdoor urban environments in comparison with regulatory limits

Damiano Urbinello [a,b,c], Wout Joseph [c], Anke Huss [d], Leen Verloock [c], Johan Beekhuizen [d], Roel Vermeulen [d], Luc Martens [c], Martin Röösli [a,b,*]

[a] *Swiss Tropical and Public Health Institute, Department of Epidemiology and Public Health, Socinstrasse 57, CH-4002 Basel, Switzerland*
[b] *University of Basel, Basel, Switzerland*
[c] *Department of Information Technology, Ghent University/iMinds, Gaston Crommenlaan 8, B-9050 Ghent, Belgium*
[d] *Institute for Risk Assessment Sciences, Department of Environmental Epidemiology, Utrecht University, Yalelaan 2, Utrecht, NL-3508 TD, The Netherlands*

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ABSTRACT

Background: Concerns of the general public about potential adverse health effects caused by radio-frequency electromagnetic fields (RF-EMFs) led authorities to introduce precautionary exposure limits, which vary considerably between regions. It may be speculated that precautionary limits affect the base station network in a manner that mean population exposure unintentionally increases.
Aims: The objectives of this multicentre study were to compare mean exposure levels in outdoor areas across four different European cities and to compare with regulatory RF-EMF exposure levels in the corresponding areas.
Methods: We performed measurements in the cities of Amsterdam (the Netherlands, regulatory limits for mobile phone base station frequency bands: 41–61 V/m), Basel (Switzerland, 4–6 V/m), Ghent (Belgium, 3–4.5 V/m) and Brussels (Belgium, 2.9–4.3 V/m) using a portable measurement device. Measurements were conducted in three different types of outdoor areas (central and non-central residential areas and downtown), between 2011 and 2012 at 12 different days. On each day, measurements were taken every 4 s for approximately 15 to 30 min per area. Measurements per urban environment were repeated 12 times during 1 year.
Results: Arithmetic mean values for mobile phone base station exposure ranged between 0.22 V/m (Basel) and 0.41 V/m (Amsterdam) in all outdoor areas combined. The 95th percentile for total RF-EMF exposure varied between 0.46 V/m (Basel) and 0.82 V/m (Amsterdam) and the 99th percentile between 0.81 V/m (Basel) and 1.20 V/m (Brussels).
Conclusions: All exposure levels were far below international reference levels proposed by ICNIRP (International Commission on Non-Ionizing Radiation Protection). Our study did not find indications that lowering the regulatory limit results in higher mobile phone base station exposure levels.

1. Introduction

The introduction and development of wireless telecommunication technologies have led to a substantial increase in radio-frequency electromagnetic field (RF-EMF) exposure in the last two decades (Frei et al., 2009; Joseph et al., 2010; Röösli et al., 2010a), resulting in a fundamental change of population-based exposure patterns to RF-EMFs.

This growth and ubiquitous use of wireless technology in society have raised public concerns regarding potential adverse health effects from RF-EMF exposure (Blettner et al., 2008; Schreier et al., 2006). This has pressured some countries (e.g., Switzerland and Belgium) to lower the precautionary regulatory exposure limits, whereas other countries (e.g., the Netherlands) retained exposure limits as proposed by the International Commission on Non-Ionizing Radiation Protection (ICNIRP).

Intuitively, lowering standard limits is expected to decrease exposure of the population by lowering the output powers of antennas. However, lower regulatory limits could affect the base station network configuration in a way that more base stations might be required to compensate lower output powers of antennas. Although a denser network may reduce maximum exposure levels, total average exposure

* Corresponding author at: Swiss Tropical and Public Health Institute, Department of Epidemiology and Public Health, University of Basel, Socinstrasse 57, Basel, CH-4002, Switzerland. Tel.: +41 61 284 83 83; fax: +41 61 284 85 01.
E-mail address: martin.roosli@unibas.ch (M. Röösli).

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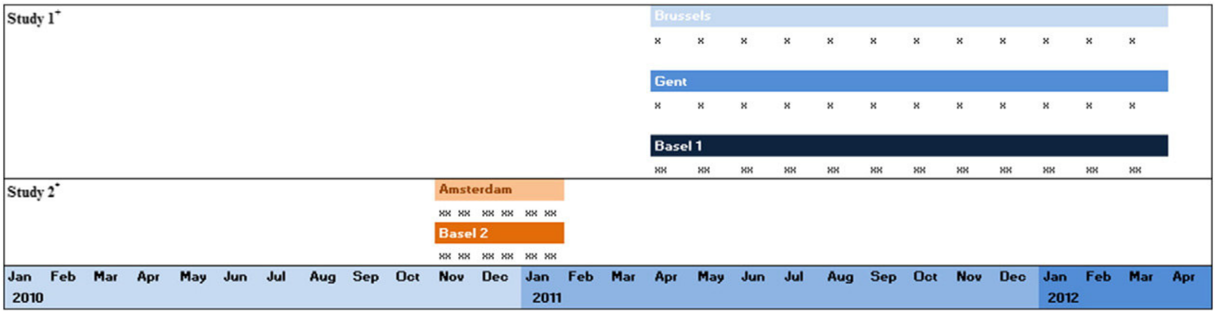

Fig. 1. Overview of data collection periods in all study cities. + Data collection: 2 days per week/each month/during 12 months. Measurements included 3 outdoor areas: central and non-central residential areas and downtown. *Data collection: 2 days per week/each 2 weeks/during 3 months. Measurements included 3 outdoor areas: central and non-central residential areas and downtown.

of the population may increase because of a higher network density. Furthermore, in a denser network mast height may be lowered and/or tilt of the antennas may be increased, producing higher RF-EMF exposure levels at the surface where people are. Thus, precautionary limits might affect exposure even in a counter-intuitive way and result in an increased mean exposure in the everyday environment where people spend their time. A denser network is also expected to affect the output power of mobile phones: the phones' output power is optimized, i.e., reduced, while an optimal connection can be maintained. However, if handovers (i.e. changing the communicating base station during an active call while moving) occur (Lin et al., 2002; Urbinello and Röösli, 2013), the output power of GSM (Global System for Mobile Communication) mobile phones returns to the maximum (Erdreich et al., 2007; Gati et al., 2009) since they radiate with full power during connection establishment and down-regulate as soon as connection has been established. UMTS (Universal Mobile Telecommunication System) phones, in contrast, have an adaptive regulation and thus radiate with lower power. The denser the network, the more handovers or location area updates have to be expected. A recent European study with software modified mobile phones found that the average output power was approximately 50% of the maximal value, and that output power varied up to a factor 2 to 3 between countries and network operators (Vrijheid et al., 2009).

So far, an evaluation of the impact of standard limits on the population's exposure has not been evaluated since comparable measurement data from countries with different standard limits were lacking. Such a comparison needs a substantial amount of data from different areas that are collected with the same methodology. Different studies have been conducted comparing RF-EMF exposure levels with measurement devices (exposimeter) in different microenvironments and countries (Bolte and Eikelboom, 2012; Frei et al., 2009; Joseph et al., 2008, 2010; Thuróczy et al., 2008; Viel et al., 2009). However, in these studies methods differed between cities concerning recruitment process of volunteers performing measurements, data analysis and/or data collection procedures: e.g. in some studies, participants carried an exposimeter during their activities and were allowed to use their own mobile phone, which influences RF-EMF exposure even if the mobile phone is in stand-by mode (Urbinello and Röösli, 2013); while in others they were not allowed to do so.

The objectives of this multicentre study were to compare RF-EMF mean exposure levels in different outdoor urban environments and to evaluate the impact of regulatory limits on RF-EMF outdoor exposure levels across European cities in terms of 95th and 99th percentiles.

Table 1
National and local directives of regulatory RF-EMF exposure limits for the four cities.

Frequency	Basel[a]	Ghent[b]	Brussels[c]	Amsterdam[d]
900 MHz	4 V/m	3 V/m	2.9 V/m	41 V/m
1800 MHz	6 V/m	4.2 V/m	4.1 V/m	58 V/m
2100 MHz	6 V/m	4.5 V/m	4.3 V/m	61 V/m

[a] Regulatory exposure limit per base station for sensitive areas: living rooms, school rooms, kindergarten, hospitals, nursing homes, places of employment, children's and school playgrounds.

[b] Regulatory exposure limit per antenna: valid for indoor places and children's playgrounds. These regulatory limits are estimated by calculating $0.1 * \sqrt{f}$ (with f as the frequency in Hz) for the frequency range between 400 MHz and 2 GHz and 4.48 V/m for 2 GHz to 10 GHz. There is also a limit for cumulative exposure of 21 V/m (at 900 MHz, frequency dependent).

[c] Regulatory exposure limit for cumulative RF-EMF exposure: valid at all public availability places (exceptions for various technologies).

[d] Regulatory exposure limit for cumulative RF-EMF exposure.

2. Methods

Data collection took place in several European cities, namely Basel (Switzerland), Ghent and Brussels (Belgium), and Amsterdam (the Netherlands). All measurements are based on a common measurement protocol.

2.1. Definition of urban environments and data collection

Measurements were conducted in different outdoor urban environments for typically 15 to 30 min per area. The type of area was matched across countries in order to enable a direct comparison. We included central residential areas, located in zones with higher buildings (4 to 5 floors) and considerable road traffic as well as numerous people on the sidewalks. Non-central residential areas are situated outside the city centre in quiet residential zones with building heights of 2 to 3 floors and relatively large proportions of green space compared to central residential and downtown areas. Downtown areas represent the city centre with a busy pedestrian zone.

We performed two separate personal measurement studies. In study 1, repeated measurements were done in Basel (denoted as Basel 1), Ghent and Brussels on either Wednesday or Thursday between April 2011 and March 2012. Data were collected in the first week of each month in Basel, and preferably in the third week of each month in Ghent and Brussels. Measurements were shifted by 1 week in case measurements could not be performed in the first and third week, respectively. The exposimeter was carried on the rear of the body in a bag.

In study 2, repeated measurements on the same days were carried out in Basel (denoted as Basel 2) and Amsterdam every second week on Wednesday and Thursday between 10th November 2010 and 27th January 2011 (Fig. 1) (Urbinello et al., 2014). In Basel, the exposimeter was placed in a pushchair cart and in Amsterdam in a bike cart. In this way, measurements were taken with a distance of around 1 m away from the body and at a height of 1 m above ground. In study 2, the paths in Basel differed from the paths in study 1, but the areas were the same.

Table 2
Summary statistics of all frequency bands combined, mobile phone base station (downlink) and handset radiation (uplink) for each city and outdoor area, ordered by increasing regulatory limit. Values are displayed as electric field strength (V/m).

	All outdoor areas combined	Central residential area	Non-central residential area	Downtown
	Arithmetic mean (95% CI)	Arithmetic mean (95% CI)	Arithmetic mean (95% CI)	Arithmetic mean (95% CI)
Total				
Brussels	0.41 (0.36, 0.46)	0.39 (0.13, 0.53)	0.24 (0.20, 0.27)	0.58 (0.49, 0.65)
Ghent	0.32 (0.29, 0.34)	0.42 (0.39, 0.46)	0.17 (0.15, 0.18)	0.32 (0.29, 0.35)
Basel 1	0.33 (0.28, 0.37)	0.16 (0.14, 0.18)	0.21 (0.17, 0.25)	0.49 (0.42, 0.54)
Basel 2	0.25 (0.24, 0.26)	0.26 (0.05, 0.37)	0.21 (0.19, 0.22)	0.34 (0.30, 0.38)
Amsterdam	0.44 (0.43, 0.45)	0.37 (0.35, 0.40)	0.40 (0.38, 0.42)	0.57 (0.55, 0.59)
Total downlink				
Brussels	0.35 (0.29, 0.39)	0.22 (0.17, 0.25)	0.23 (0.19, 0.26)	0.51 (0.41, 0.59)
Ghent	0.27 (0.25, 0.29)	0.36 (0.33, 0.39)	0.15 (0.14, 0.16)	0.27 (0.25, 0.29)
Basel 1	0.31 (0.27, 0.35)	0.14 (0.12, 0.16)	0.20 (0.16, 0.24)	0.47 (0.40, 0.53)
Basel 2	0.22 (0.21, 0.23)	0.18 (0.16, 0.19)	0.20 (0.19, 0.21)	0.30 (0.30, 0.31)
Amsterdam	0.41 (0.40, 0.43)	0.31 (0.28, 0.33)	0.36 (0.34, 0.38)	0.51 (0.49, 0.52)
Total uplink				
Brussels	0.17 (0.05, 0.24)	0.27 (0, 0.45)	0.04 (0.02, 0.05)	0.20 (0.16, 0.23)
Ghent	0.06 (0.04, 0.08)	0.04 (0.03, 0.04)	0.03 (0.02, 0.03)	0.11 (0.06, 0.14)
Basel 1	0.06 (0.05, 0.07)	0.05 (0.04, 0.06)	0.02 (0.02, 0.03)	0.09 (0.07, 0.10)
Basel 2	0.06 (0.05, 0.06)	0.18 (0, 0.32)	0.07 (0.00, 0.11)	0.14 (0.00, 0.22)
Amsterdam	0.09 (0.08, 0.10)	0.16 (0.14, 0.18)	0.12 (0.11, 0.12)	0.17 (0.16, 0.18)

All measurements were conducted by the same study assistant in all cities except in Amsterdam. The mobile phone of the person taking the measurements was turned off while measuring and all measurements were carried out during daytime. Fig. 1 summarizes the study procedure in the different cities.

2.2. Study instruments

RF-EMF measurements in Basel, Ghent and Brussels were performed using the EME Spy 120 (ES 120) from SATIMO (SATIMO, Courtaboeuf, France, http://www.satimo.fr/), enabling to quantify personal exposure at 12 separate frequency bands. Frequency bands for the ES 120 range from FM radio (frequency modulation; 88–108 MHz) to W-LAN (wireless local area network; 2.4–2.5 GHz). In Amsterdam, the EME Spy 140 (ES 140) was used. The measurement interval was set to 4 s in order to collect a large number of data points.

A GPS (Global Positioning System) logger (GPS Sport 245 from Holux) was used to log locations at 10 second intervals in Basel, Ghent and Brussels, and a Garmin Oregon 550 (Garmin Inc., Olathe, KS, USA) in Amsterdam. The Swiss Federal Institute of Technology (ETH Zurich) developed a smart phone based application to log the time in all urban environments by registering start and ending of measurements in a specific microenvironment enabling the linkage of measurements to the specific area.

All devices were calibrated in September 2010, April 2011, and December 2011.

2.3. Statistical analyses

The lower detection limit of the ES 120 is 0.0067 mW/m^2 and 0.000067 mW/m^2 for the ES 140 (corresponding to electric field strengths of 0.05 V/m and 0.005 V/m, respectively). In order to have comparable results for Amsterdam, data were censored at 0.05 V/m and arithmetic mean values, with 95% confidence interval (CI), for each area and frequency per measurement day were calculated using the robust regression on order statistics (ROS) algorithm (Röösli et al., 2008). If less than three measurements were above the detection limit for a given area and frequency band, the arithmetic mean value was set to 0.000265 mW/m^2 (0.01 V/m). All calculations were conducted using power flux density values (i.e. power flux per area, denoted as power densities) in W/m^2 and then back-transformed to electric field strengths (V/m). For the analyses we considered three relevant frequency groups: i) total RF-EMF exposure: sum of mean power densities of all frequency bands without DECT (Digital Enhanced Cordless Telecommunications). We excluded DECT since it is not a relevant source in outdoor areas and calibration showed cross-talk with nearby bands; ii) mobile phone base station exposure: sum of mean power densities of all downlink frequencies (GSM900 (925–960 MHz), GSM1800 (1805–1880 MHz) and UMTS (2110–2170 MHz)); and iii) mobile phone handset exposure: sum of mean power densities of all uplink frequencies (GSM900 (880–915 MHz), GSM1800 (1710–1785 MHz) and UMTS (1920–1980 MHz)).

The data distributions including the occurrence of high exposure values in the four cities were evaluated with the cumulative density function (CDF).

2.4. Regulatory limits

In the Netherlands, regulatory levels are adopted from the ICNIRP guidelines (ICNIRP, 1998) (Table 1). The ICNIRP regulatory limits are frequency-dependent; 41 V/m for 900 MHz, 58 V/m for 1800 MHz and 61 V/m for 2100 MHz.

In Switzerland, the ICNIRP guidelines are also implemented. In addition, frequency-dependent precautionary exposure limits have been set (ONIR, 1999). The ONIR (Ordinance relating to Protection from Non-Ionizing Radiation) limits apply to the emission from one single base station and are only relevant for sensitive areas where persons spend most of their time, such as residences, schools, kindergartens, hospitals, nursing homes, workplaces, children's and school playgrounds. The ONIR precautionary limits of electric field strengths are 10 times lower than the ICNIRP guidelines (Table 1). In Ghent, precautionary regulatory exposure limits of the Flemish region (Ordinance of the Flemish Region of Nov., 2010) are valid for exposure per base station and apply to indoor places and children's playgrounds: 3 V/m at 900 MHz, 4.2 at 1800 MHz and 4.5 V/m at 2100 MHz (Table 1). These precautionary regulatory limits are estimated by calculating $0.1 * \sqrt{f}$ (with f as the frequency in Hz) for the frequency range between 400 MHz and 2 GHz and 4.5 V/m for >2 GHz to 10 GHz. In Brussels, limits of the Brussels Capital Region (Ordinance of the Brussels Capital Region of 14 March, 2007) are valid at all public places in total (i.e. cumulative exposure[1]); precautionary regulatory limits for

[1] In Ghent, Flanders there is also a limit for cumulative exposure of 21 V/m (at 900 MHz, frequency dependent).

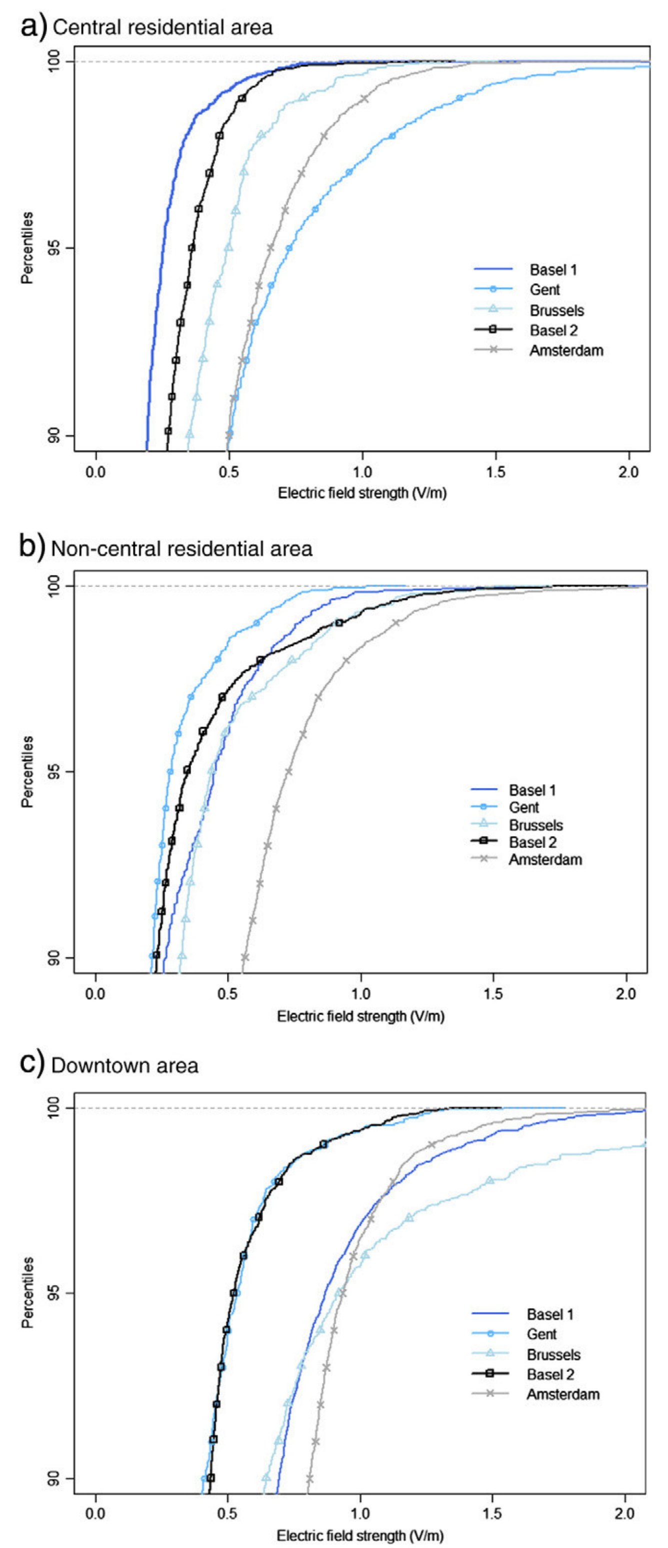

Fig. 2. Cumulative density function (CDF) plots of the total downlink electric field strength (V/m) for central residential (a), non-central residential (b) and downtown (c) areas.

frequencies between 400 MHz and 2 GHz are calculated using the formula $f/40{,}000$ (W/m^2) (with f as the frequency in Hz; corresponds to $\sqrt{(f/40,000\ [W/m2] * 377)}$ on electric field strength). For frequencies between 2 GHz and 300 GHz, exposure values may not exceed 4.3 V/m (corresponds to 0.05 W/m^2 on power flux density level) (Table 1). According to the adopted limits in the different countries, regulatory exposure limits are most strict in Brussels and least stringent in Amsterdam (Table 1).

3. Results

3.1. General results and cross-comparison between countries

In study 1, a total of 8304 data points per frequency band were collected for Basel 1, 8909 for Ghent and 8165 for Brussels during 1 year for all outdoor areas combined. In study 2, we collected 16,401 and 22,532 measurements per frequency band in Basel and Amsterdam, respectively, over a period of 3 months for all areas combined.

Average total RF-EMF exposure over the whole study period and all outdoor areas combined varied between 0.25 V/m (Basel 2) and 0.44 V/m (Amsterdam). Exposure values tended to be higher in the downtown areas ranging from 0.32 V/m (Ghent) to 0.58 V/m (Brussels), whereas exposure levels in residential areas (non-central and central residential) were somewhat lower (0.16 V/m (Basel 2) to 0.42 V/m (Ghent)). Total RF-EMF exposure in outdoor areas was mainly driven by mobile phone base station radiation exposure causing levels between 0.22 V/m (Basel 2) and 0.41 V/m (Amsterdam) for all areas combined, whereby influence of mobile phone handsets was marginal: 0.06 V/m (Basel 1, Basel 2, and Ghent) to 0.17 V/m (Brussels) (Table 2).

3.2. Data distribution of high exposure levels and investigation of the impact of regulatory limits on RF-EMF exposure

In order to explore the distribution of high exposure levels, Fig. 2 and Table 3 show the 95th and 99th percentiles. In central residential areas, the 95th percentile ranged between 0.27 V/m (99th percentile: 0.45 V/m) in Basel 1 and 0.73 V/m in Ghent (99th percentile: 1.37 V/m), in non-central residential areas between 0.29 V/m (0.61 V/m) in Ghent and 0.73 V/m (1.13 V/m) in Amsterdam. Highest exposure levels occurred in the downtown areas ranging between 0.52 V/m (Basel 2) and 0.94 V/m (Amsterdam) for the 95th percentile and between 0.87 V/m (Ghent and Basel 2) and 2.08 V/m (Brussels) for the 99th percentile (Table 3 and Fig. 2c).

Fig. 3 shows mobile phone base station exposure as a function of the corresponding regulatory limit for arithmetic mean levels averaged over the entire study period. In the central residential area of Ghent (0.36 V/m) and downtown areas of Brussels (0.51 V/m) and Basel 2 (0.47 V/m) exposure levels were of similar magnitude as in Amsterdam (central residential area: 0.31 V/m; downtown: 0.51 V/m) despite the lower regulatory limits in Ghent, Brussels and Basel.

4. Discussion

This paper analysed RF-EMF exposure in different outdoor areas and evaluated whether lower regulatory limits have an impact on ambient exposure across several European cities. In contrast to our speculation, our study did not find indications that lowering regulatory limits results in higher mobile phone base station exposure levels. Exposure levels were highly spatially variable and varied considerably between different areas within as well as between cities. For example, within city mobile phone base station exposure in Basel varied between 0.14 V/m (central residential area) and 0.47 V/m (downtown). Also, between cities substantial differences were observed for the same type of areas. In central residential areas mean exposure ranged from 0.14 V/m (Basel 1) to 0.36 V/m (Ghent), in non-central residential areas from 0.15 V/m (Ghent) to 0.36 V/m (Amsterdam) and in downtown areas from 0.27 V/m (Ghent) to 0.51 V/m (Brussels and Amsterdam).

Table 3
Overview of total RF-EMF exposure values for the 95th and 99th percentile in outdoor areas. Values are displayed as electric field strength (V/m).

	All areas combined	Central residential area	Non-central residential area	Downtown
95 percentile				
Basel 1	0.66	0.27	0.48	0.89
Ghent	0.53	0.73	0.29	0.54
Brussels	0.66	0.50	0.44	0.92
Basel 2	0.46	0.36	0.34	0.52
Amsterdam	0.82	0.66	0.73	0.94
99 percentile				
Basel 1	1.08	0.45	0.83	1.40
Ghent	1.03	1.37	0.61	0.87
Brussels	1.20	0.78	0.92	2.08
Basel 2	0.81	0.55	0.92	0.87
Amsterdam	1.14	1.01	1.13	1.27

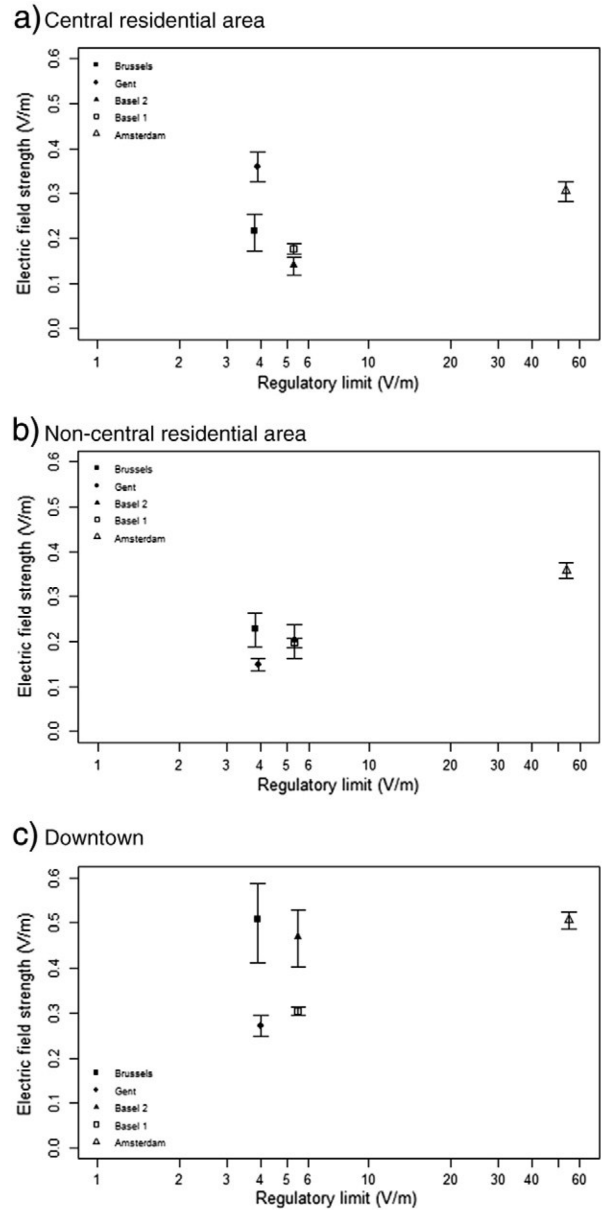

Fig. 3. Scatter plots indicating mobile phone base station exposure levels with corresponding 95% confidence intervals across all cities in relation to regulatory limits for central residential (a), non-central residential (b) and downtown (c) areas.

4.1. Strengths and limitations

This is the first study investigating the impact of different regulatory limits on RF-EMF exposure in different outdoor environments using a common data collection procedure across four European cities. Previous international studies extracted data from multiple studies using different data collection or analysis procedures (Joseph et al., 2010), limiting a direct comparison between countries.

A further strength of our study was that the own mobile phone was turned off during measurements, enabling the association of mobile phone handset exposure to be attributable to other peoples' mobile phone which was not the case in previous studies (Frei et al., 2009; Viel et al., 2009).

Our study has also limitations; due to practical reasons we could not measure at the same time and apply the exact same procedures in all 4 cities. For instance, the exposimeter used for measurements in Amsterdam was not of the same type (ES 140) and differed in the lower detection limit from the exposimeter used in Belgium and Switzerland. However, we censored this data at the same detection limit as the data collected with the ES 120 (i.e. 0.05 V/m) to obtain comparable results and we excluded the two additional frequency bands (i.e. WiMax and W-LAN 5G) as well as DECT, which was excluded from all data due to cross-talk interferences (Lauer et al., 2012).

A further limitation is the inclusion of only four cities with three areas per city into the study. Thus, random data variability may play a role and additional data from more cities would allow drawing firmer conclusions.

Since we took all measurements on two working days (Wednesday and Thursday) and during daytime, we did not capture differences in exposure between working days and weekends, or between daytime and evening. However, we suspect that even though there could be differences in exposure levels at different times of the day; these are probably similar across the different cities. Furthermore, temporal variability has been found to be low across days of the week (Beekhuizen et al., 2013).

4.2. Interpretation

All RF-EMF exposure levels were far below ICNIRP reference levels. So far, no health effects could consistently be demonstrated below this level (Röösli et al., 2010b). Nevertheless, there is some uncertainty about long term health effects at low exposure levels and minimizing exposure to RF-EMFs has been recommended (Berg-Beckhoff et al., 2009; Blettner et al., 2008; Neubauer et al., 2007; WHO, 2010) and many countries have thus introduced precautionary limits. Whether such measures are effective to reduce population exposure has not been evaluated so far. The consequences of precautionary limits on the exposure situation are difficult to predict because more stringent regulations affect the base station network configuration. It seems plausible that high exposure values are reduced by precautionary limits but mean exposure may even be increased due to the higher network density with more microcells installed close to where the population spends its time. Our study, however, did not find any indications for this. Conversely, across all areas mean exposure levels were highest in Amsterdam which might indicate that precautionary levels indeed reduce population's mobile phone base station exposure. However, in area specific comparisons, levels in Amsterdam were similar to other cities except for the non-central residential area. The most relevant exposure effect if more base stations are installed might be the exposure reduction from the own mobile phone due to an optimized power control. However, our study did not find any indications that uplink exposure levels from mobile phones were related to the level of the regulatory limits, although in order to accurately assess personal exposure, other techniques would be needed to evaluate whether the base station network configuration affects the output power of the phones.

Interestingly, also high exposure levels (95th and 99th percentiles) were not related to the level of the regulatory limits as one would primarily expect. The 99th percentile was highest in Brussels, where most stringent regulatory limits were implemented. It has to be emphasized that our analysis is based on four cities only and alternative explanations should be considered. We tried to match characteristics of the selected areas across the cities. Nevertheless, the fact that exposure tended to be higher in Amsterdam may reflect the impact of population density, building characteristics or the choice of the measurement path in an area.

One could argue that the level of RF-EMF exposure in the population is not relevant as long as the reference levels, where health effects have been established, are not exceeded. However, in terms of long term health effects some uncertainty exists and thus minimizing exposure may reduce this uncertainty. For compliance with the regulatory limits most critical places are on the top floor of buildings, close and in direct line of sight of mobile phone base stations. As we measured only on street level, we cannot exclude that higher exposure levels can occur at such sites in cities with higher regulatory limits. If of concern, such high exposures could be reduced by limiting the output power of base stations.

4.3. Conclusion

Our study suggests that the introduction of precautionary limits does not unintentionally increase the mean RF-EMF exposure of the population.

Conflict of interest

The authors declare no conflict of interest.

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7 Temporal variation of RF-EMF exposure

Article 4: Temporal trends of radio-frequency electromagnetic field (RF-EMF) exposure in everyday environments across European cities

Damiano Urbinello[1,2,3], Wout Joseph[3], Leen Verloock[3], Luc Martens[3] and Martin Röösli[1,2]

1 Swiss Tropical and Public Health Institute
2 University of Basel, Switzerland
3 Department of Information Technology, Ghent University / iMinds

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Temporal trends of radio-frequency electromagnetic field (RF-EMF) exposure in everyday environments across European cities

Damiano Urbinello [a,b,c], Wout Joseph [c], Leen Verloock [c], Luc Martens [c], Martin Röösli [a,b,*]

[a] Swiss Tropical and Public Health Institute, Department of Epidemiology and Public Health, Socinstrasse 57, CH-4002 Basel, Switzerland
[b] University of Basel, Basel, Switzerland
[c] Department of Information Technology, Ghent University/iMinds, Gaston Crommenlaan 8, B-9050 Ghent, Belgium

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ABSTRACT

Background: The rapid development and increased use of wireless telecommunication technologies led to a substantial change of radio-frequency electromagnetic field (RF-EMF) exposure in the general population but little is known about temporal trends of RF-EMF in our everyday environment.
Objectives: The objective of our study is to evaluate temporal trends of RF-EMF exposure levels in different microenvironments of three European cities using a common measurement protocol.
Methods: We performed measurements in the cities of Basel (Switzerland), Ghent and Brussels (Belgium) during one year, between April 2011 and March 2012. RF-EMF exposure in 11 different frequency bands ranging from FM (Frequency Modulation, 88 MHz) to WLAN (Wireless Local Area Network, 2.5 GHz) was quantified with portable measurement devices (exposimeters) in various microenvironments: outdoor areas (residential areas, downtown and suburb), public transports (train, bus and tram or metro rides) and indoor places (airport, railway station and shopping centers). Measurements were collected every 4 s during 10–50 min per environment and measurement day. Linear temporal trends were analyzed by mixed linear regression models.
Results: Highest total RF-EMF exposure levels occurred in public transports (all public transports combined) with arithmetic mean values of 0.84 V/m in Brussels, 0.72 V/m in Ghent, and 0.59 V/m in Basel. In all outdoor areas combined, mean exposure levels were 0.41 V/m in Brussels, 0.31 V/m in Ghent and 0.26 V/m in Basel.

Within one year, total RF-EMF exposure levels in all outdoor areas in combination increased by 57.1% ($p < 0.001$) in Basel by 20.1% in Ghent ($p = 0.053$) and by 38.2% ($p = 0.012$) in Brussels. Exposure increase was most consistently observed in outdoor areas due to emissions from mobile phone base stations. In public transports RF-EMF levels tended also to increase but mostly without statistical significance.
Discussion: An increase of RF-EMF exposure levels has been observed between April 2011 and March 2012 in various microenvironments of three European cities. Nevertheless, exposure levels were still far below regulatory limits of each country. A continuous monitoring is needed to identify high exposure areas and to anticipate critical development of RF-EMF exposure at public places.

1. Introduction

The introduction and development of new wireless telecommunication technologies led to a substantial change of radio-frequency electromagnetic field (RF-EMF) exposure patterns. To meet technological requirements and advantages of newly launched wireless devices, the telecommunication network has to be expanded and optimized. The use of new mobile technologies has increased and is still further augmenting, whereas transmission of data through the mobile internet became more efficient resulting in lower RF-EMF emissions per transmitted byte of data. At this point, it is unclear what the net effect on exposure level is and whether exposure is increasing in everyday environments over time.

In the last few years, several measurement studies have been conducted characterizing RF-EMF exposure levels in different microenvironments and comparing exposure in different cities using personal exposimeters (Berg-Beckhoff et al., 2009; Bolte and Eikelboom, 2012; Frei et al., 2009; Joseph et al., 2010, 2008; Thuróczy et al., 2008; Viel et al., 2009). These studies found that RF-EMF levels in the everyday environment are far below the regulatory limits. Several studies examined short-term temporal variability of RF-EMF exposure during one day (Mahfouz et al., 2011, 2013;

* Corresponding author at: Swiss Tropical and Public Health Institute, Department of Epidemiology and Public Health, University of Basel, Socinstrasse 57, Basel CH-4002, Switzerland. Fax: +41 61 284 85 01.
E-mail address: martin.roosli@unibas.ch (M. Röösli).

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Manassas et al., 2012; Miclaus et al., 2013) or up to one week (Joseph and Verloock, 2010; Joseph et al., 2009; Vermeeren et al., 2013) addressing variation between daytime and nighttime or during weekdays and weekends (Joseph et al., 2009). However, studies evaluating temporal trends over longer time periods as one year are lacking so far. Frei et al. (2009) stated that introduction of mobile phone technology has resulted in a 10-fold increase of RF-EMFs at outdoor areas compared to the time period before when broadcast transmitting was the most relevant source (Frei et al., 2010; Mohler et al., 2012).

To be reliable, such a temporal trend analysis needs a substantial amount of data from different environments that are collected with the same methodology (Joseph et al., 2010). Repeated measurements with portable measurement devices in various microenvironments allow to efficiently collect a high number of measurements per microenvironment (Röösli et al., 2010).

The aim of this microenvironmental measurement study was to characterize RF-EMF exposure levels in typical everyday environments and to investigate temporal trends in outdoor areas, public transports, and indoor settings of three different European cities.

2. Methods

Data collection took place in Basel (Switzerland), Ghent and Brussels (Belgium) between April 2011 and March 2012. All measurements are based on a common measurement protocol adopted in each city in order to enable direct comparisons.

2.1. Definition of microenvironments and measurement procedures in different cities

We included characteristic everyday environments in outdoor areas, where measurements occurred exclusively outside buildings in free space, public transports (train, bus, tram and metro) and indoor settings (2 different shopping centers per city, main railway station of each city and the airports of Basel and Brussels) in our study areas (Table 1). Measurements in outdoor areas include central- and non-central residential areas, downtown areas and suburban areas. Areas were matched across cities according to several criteria: central residential areas were located in zones with higher buildings (4–5 floors) and more traffic as well as more people on sidewalks. Non-central residential areas are, in contrast, situated outside the city center in quiet residential zones with building heights up to 3 floors and relatively large parts of green space compared to central residential and downtown areas. Downtown areas represent the city center with busy pedestrian zones. Data was further collected in public transports such as express trains (train rides included measurements between Aarau and Basel (Switzerland), Ghent and Brussels (Belgium)), buses (bus rides in each city between the suburban area and the inner city), trams (various tram rides within the city) and metro (only within the city of Brussels, as there are no trams). Indoor settings included Basel's and Brussels' airports, railway stations in Basel (Basel main station), Ghent (Ghent-Sint-Pieters main station) and Brussels (Central station – Gare Centrale) and shopping centers (two major shopping malls per city).

Measurements were conducted once every month during one year. Data were collected by the same research assistant each time, by walking along the same routes using the same time schedules each month.

In Basel, data were collected in the first week of each month on Wednesdays and Thursdays in the morning between 7:30 and 11:40. In Ghent and Brussels, measurements were conducted in the third week of each month, on Wednesdays in Ghent (including measurements at Brussel's airport), between 8:45 and 16:45 and on Thursdays in Brussels, between 8:40 and 17:40 (Table 1). Measurements were shifted by one week in case data collection could not be performed in the first and third week. The exposimeter was carried on the rear of the body in a bag. The exposimeter was fixed in a bag and placed vertically. During measurements in public transports, the bag was placed either in front of the study assistant or next to him on a free seat when seating (typically in trains, buses and metros) or on the rear of the body if the assistant had to stand (usually in trams). In the latter case, an attempt was made to have no persons in close vicinity. Measurement duration in the same microenvironment was always the same and ranged between 10 and 60 min for different environments (Table 1). For this duration of measurements within a microenvironment we have previously observed to produce reproducible and reliable results in the sense that average exposures within a type of microenvironment approach a stable mean value (Beekhuizen et al., 2013; Urbinello et al., 2014). The mobile phone was turned off during data collection. All measurements occurred during daytime.

2.2. Study instruments

We performed our measurements using an exposimeter of the type EME Spy 120 from SATIMO (SATIMO, Courtaboeuf, France, http://www.satimo.fr/), capable to quantify personal RF-EMF exposure on 12 different frequency bands: Frequency Modulation (FM, 88–108 MHz); Television (TV, 174–223 MHz and 470–830 MHz); Terrestrial Trunked Radio (TETRA, 380–400 MHz); Global System for Mobile Communications at 900 MHz downlink (i.e. communication from base station to mobile phone, 925–960 MHz) and uplink (i.e. communication from mobile phone to base station, 880–915 MHz), GSM at 1800 MHz (GSM1800) downlink (1805–1880 MHz) and uplink (1710–1785 MHz); Digital Enhanced Cordless Telecommunications (DECT, 1880–1900 MHz); Universal Mobile Telecommunications System (UMTS) downlink (2110–2170 MHz) and uplink (1920–1980 MHz) and Wireless Local Area Networks (WLAN, 2400–2500 MHz). The exposimeter has a lower detection limit of 0.0067 mW/m^2 (corresponding to 0.05 V/m of electric field strength) and an upper detection limit of 66.3 mW/m^2 (5 V/m). The measurement interval was configured to 4 s in order to collect a maximal number of data points, generating robust datasets. An application on a smartphone was developed by the Swiss Federal Institute of Technology (ETH Zurich) which allowed recording the time by clicking on start and stop when beginning and finishing the measurements in a microenvironment, respectively. The smartphone was in flight mode while taking the measurements preventing exposure contribution from the own mobile handset. The device was calibrated on October 2010, April 2011, and December 2011 at the ETH Zurich showing temporal fairly stable calibration factors. However, although GSM1800 downlink and UMTS uplink were correctly detected by the exposimeter, we observed that the presence of these bands affected the DECT measurements (cross-talk). Since the presence of DECT fields is negligible in outdoor areas and public transports (no cordless phones) we omitted this frequency range. DECT is also expected to be of minor importance in the indoor settings we included, i.e. shopping centers, airport and train station. Thus, our results are still comparable with those of other studies that have DECT included in such microenvironments. On the other hand, the calibration revealed that DECT signals were also taken up in the UMTS uplink frequency band. However, since little DECT was present in our study area, this did not result in a bias.

2.3. Statistical analyses

To take into account that a large proportion of data points were below the lower detection limit of the exposimeter, arithmetic mean values have been calculated for each measurement day per frequency and per microenvironment with the robust regression on order statistics (ROS) algorithm using the statistical software R Version 3.0.1 (www.r-project.org) (Röösli et al., 2008). A full description of the analysis method can be found in Helsel (2005). All calculations were made on power flux density levels (μW/cm^2) and then back-transformed to electric field strength (V/m). Annual mean values per microenvironment were obtained by averaging these daily mean values. For the analyses we considered three relevant frequency groups: i) total RF-EMF exposure: sum of mean power flux densities of all frequency bands apart from DECT (Digital Enhanced Cordless Telecommunications). We excluded DECT, since calibration showed cross-talk with nearby bands, i.e. GSM1800; ii) mobile phone base station exposure: sum of mean power flux densities of all downlink frequencies (GSM900 (925–960 MHz), GSM1800 (1805–1880 MHz) and UMTS (2110–2170 MHz)); and iii) mobile phone handset exposure: sum of mean power flux densities of all uplink frequencies (GSM900 (880–915 MHz), GSM1800 (1710–1785 MHz) and UMTS (1920–1980 MHz)).

Temporal trends were examined using linear regression models. Month as integer was introduced as linear term in the models. To achieve normally distributed residuals, all calculations were done on the log-transformed power flux density scale and model coefficients were back-transformed thus reflecting annual changes of the geometric mean value on the electric field scale (V/m). Trend analyses of combined microenvironments (all outdoor areas and all public transports combined) were based on multilevel mixed-effects models with type of microenvironment as cluster variable. Trend analyses of single microenvironments were conducted using log-linear regressions. Analyses were conducted with STATA version 12.1 (StataCorp, College Station, TX, USA).

3. Results

3.1. Characterization of RF-EMF exposure levels in different environments

Table 2 summarizes RF-EMF exposure levels for the different environments (outdoor areas, public transports and indoor settings) across all three cities.

Highest total RF-EMF exposure levels occurred in all public transports combined. In trains exposure levels ranged between

Table 1
Overview including the average number of data points per measurement day and microenvironment with the planned time schedule per environment and the corresponding measurement day where data collection occurred in each city.

		Average number of data points per day and per microenvironment	Path length	Estimated duration	Time ranges	Measurement day
Outdoor areas						
Central residential area	Basel	272	1.6 km	16 min	10:05–10:20	Wednesday
	Ghent	255	1.5 km	15 min	08:45–09:00	Wednesday
	Brussels	186	1.1 km	12 min	13:15–13:30	Thursday
Non-central residential area	Basel	173	1.2 km	12 min	09:20–09:35	Wednesday
	Ghent	270	1.8 km	18 min	09:40–09:55	Wednesday
	Brussels	271	1.7 km	17 min	10:45–11:00	Thursday
Downtown	Basel	248	1.5 km	15 min	10:25–10:40	Wednesday
	Ghent	217	1.3 km	13 min	12:00–12:15	Wednesday
	Brussels	224	1.1 km	12 min	13:40–13:50/14:10–14:20	Thursday
Suburb	Basel	266	1.6 km	16 min	08:40–08:55	Thursday
	Ghent	169	1.0 km	11 min	10:40–10:50	Wednesday
	Brussels	195	1.2 km	12 min	12:05–12:20	Thursday
Public transports						
Train	Basel	528			07:36–08:15	Wednesday
	Ghent	1628			13:15–14:08/14:48–15:42	Wednesday
	Brussels	1095			09:03–09:36/16:00–16:36	Thursday
Bus	Basel	1085			11:35–11:40 (Wed)/09:06–09:45 (Thu)/10:45–10:55 (Thu)	Wednesday/ Thursday
	Ghent	597			10:15–10:40/11:15–11:40	Wednesday
	Brussels	290			10:35–10:40/12:35–12:50	Thursday
Tram	Basel	281			08.33–08.36/08:55–09:00/09:05–09:14/11:10–11:15/ 12:30–12:40	Wednesday
	Ghent	195			09:25–09:35/09:55–10:00	Wednesday
Metro	Brussels	1246			09:55–10:20/11:20–11:45/11:50–12:00/13:00–13:05/ 14:50–15:05/15:25–15:35/15:40–15:45	Thursday
Indoor settings						
Airport (Basel and Brussels)	Basel	295			10:15–10:40	Thursday
	Ghent	–			–	–
	Brussels	419			14:25–14:45	Wednesday
Railway station	Basel	361			08:15–08:30/10:20–10:25	Wednesday/ Thursday
	Ghent	403			12:45–13:15	Wednesday
	Brussels	255			08:50–09:00/09:36–09:45/15:50–16:00	Thursday
Shopping centers	Basel	506			10:45–11:00 (shopping mall I)/11:15–11:30 (shopping mall II)	Wednesday
	Ghent	433			11:40–12:00 (shopping mall I)/12:15–12:30 (shopping mall II)	Wednesday
	Brussels	372			14:00–14:10 (shopping mall I)/14:20–14:35 (shopping mall II)	Thursday

0.83 V/m (Ghent) and 1.06 V/m (Brussels) and were considerably higher compared to those of other environments (Table 2a). Mobile phone handsets were the main exposure source in trains (Table 2c, Online Fig. 1b), whereas in other public transports, such as buses and trams or metros, mobile phone base stations had also a considerable impact on the exposure situation (Table 2b).

RF-EMF exposure is highly spatially variable (Table 2a and b) across different outdoor areas within one city. Highest total RF-EMF exposure occurred in downtown areas (Basel: 0.49 V/m, Brussels: 0.58 V/m) and in one central residential area (Ghent: 0.42 V/m). In contrast, lowest values were observed in central (Basel: 0.16 V/m) and non-central residential areas (Ghent: 0.17 V/m; Brussels: 0.24 V/m). In outdoor areas, highest contribution to total RF-EMF exposure originates from mobile phone base stations (Table 2b), whereas mobile phone handset exposure is negligible in outdoor areas of Basel and Ghent (<0.11 V/m), but seems to play a more important role in several areas of Brussels (Table 2c).

Exposure situation at the airport was highest compared to that of other indoor settings. Total RF-EMF exposure was highest at the railway station (0.57 V/m, Brussels) and at the airport: 0.53 V/m (Brussels) and 0.54 V/m (Basel) (Table 2a). In indoor settings, both, mobile phone base stations and handsets contributed a fair amount to total RF-EMF exposure (Table 2b and c).

3.2. Temporal trends

We observed a considerable change in RF-EMF exposure situation during the period between April 2011 and March 2012 across all cities.

Fig. 1a and b suggests a consistent increase of RF-EMF exposure in urban outdoor areas considering total RF-EMF and mobile phone base station exposure, which is the most relevant source in outdoor areas. Trend analysis using multilevel mixed effects linear models supports the graphical facts (Fig. 1b) with highly statistically significant increases in geometric mean of mobile phone base station exposure for all outdoor areas combined in Basel (64.0%, $p<0.001$), Ghent (23.6%, $p=0.021$) and Brussels (68.3%, $p<0.001$) (Table 2b). Area-specific yearly changes were also more pronounced in the Basel outdoor areas than in the corresponding areas of Ghent. In Brussels, area specific trends were heterogeneous ranging from a 26.4% increase ($p=0.377$) in the downtown area to a 120.2% ($p=0.002$) increase in the central residential area (Table 2b). Temporal increase of mobile phone

Table 2
Arithmetic mean values and yearly percentage change of total RF-EMF (a), mobile phone base station (b) and mobile phone handset (c) exposure with corresponding 95% confidence intervals (CI). Arithmetic mean values are reported as electric field strengths (V/m).

	Arithmetic means with 95% CI			Temporal change[a] (%) with 95% CI					
	Basel	Ghent	Brussels	Basel	*p*	Ghent	*p*	Brussels	*p*
a) Total RF-EMF exposure									
Outdoor									
All areas combined	0.26 (0.23, 0.29)	0.31 (0.28, 0.34)	0.41 (0.36, 0.46)	57.1 (32.4, 86.5)	< 0.001	20.1 (−0.3, 44.6)	0.053	38.2 (7.3, 77.9)	0.012
Central residential area	0.16 (0.14, 0.18)	0.42 (0.39, 0.46)	0.39 (0.13, 0.53)	63.7 (13.7, 135.5)	0.013	25.3 (−11.8, 78.0)	0.183	−8.7 (−63.4, 128.0)	0.830
Non-central residential are[a]	0.21 (0.17, 0.25)	0.17 (0.15, 0.18)	0.24 (0.20, 0.27)	87.2 (12.5, 211.6)	0.021	36.7 (−0.9, 88.5)	0.055	103.8 (53.0, 171.4)	< 0.001
Downtown	0.49 (0.42, 0.54)	0.32 (0.29, 0.35)	0.58 (0.49, 0.65)	56.5 (16.1, 110.9)	0.007	27.4 (−6.9, 74.2)	0.116	25.2 (−17.1, 89.1)	0.253
Suburb	0.17 (0.14, 0.18)	0.26 (0.18, 0.33)	0.39 (0.32, 0.45)	27.1 (−13.4, 86.7)	0.194	−4.6 (−50.2, 82.7)	0.874	56.5 (1.4, 141.6)	0.044
Public transports									
All public transports combined	0.59 (0.38, 0.74)	0.72 (0.61, 0.81)	0.84 (0.72, 0.96)	17.7 (−12.7, 58.7)	0.285	38.0 (−15.5, 125.3)	0.198	46.9 (−1.2, 118.5)	0.057
Train	0.97 (0.46, 1.29)	0.83 (0.71, 0.94)	1.06 (0.88, 1.21)	−35.0 (−81.4, 127.3)	0.461	37.6 (−37.0, 200.3)	0.384	39.1 (−17.0, 132.9)	0.185
Tram/metro[b]	0.32 (0.24, 0.39)	0.50 (0.36, 0.61)	0.70 (0.53, 0.83)	30.3 (−20.6, 113.9)	0.286	19.3 (−45.6, 161.6)	0.651	108.0 (9.3, 295.9)	0.030
Bus	0.35 (0.26, 0.42)	0.36 (0.23, 0.46)	0.37 (0.30, 0.44)	29.5 (−14.8, 96.9)	0.218	114.3 (3.2, 344.9)	0.042	40.2 (−452, 258.6)	0.453
Indoor									
Airport	0.54 (0.44, 0.62)	–	0.53 (0.45, 0.60)	64.3 (5.3, 156.3)	0.032	–	–	14.5 (−33.6 97.6)	0.592
Train station	0.34 (0.26, 0.40)	0.32 (0.23, 0.39)	0.57 (0.35, 0.72)	96.9 (−1.3, 292.7)	0.054	−1.0 (−55.7, 120.9)	0.978	65.4 (−22.2, 251.9)	0.168
Shopping centers	0.22 (0.18, 0.26)	0.32 (0.25, 0.37)	0.37 (0.30, 0.43)	100.7 (25.8, 220.3)	0.005	19.3 (−41.8, 144.8)	0.615	48.5 (−6.4, 135.7)	0.089
b) Mobile phone base station exposure									
Outdoor									
All areas combined	0.24 (0.21, 0.27)	0.27 (0.24, 0.29)	0.35 (0.29, 0.39)	64.0 (37.5, 95.6)	< 0.001	23.6 (3.3, 47.8)	0.021	68.3 (37.4, 106.3)	< 0.001
Central residential area	0.14 (0.12, 0.16)	0.36 (0.33, 0.39)	0.22 (0.17, 0.25)	69.4 (11.6, 157.1)	0.018	33.7 (−5.0, 88.2)	0.088	120.2 (44.3, 236.1)	0.002
Non-central residential are[a]	0.20 (0.16, 0.24)	0.15 (0.14, 0.16)	0.23 (0.19, 0.26)	96.5 (14.0, 238.6)	0.02	25.6 (−7.1, 69.9)	0.124	98.4 (39.3, 182.8)	0.002
Downtown	0.47 (0.40, 0.53)	0.27 (0.25, 0.29)	0.51 (0.41, 0.59)	58.4 (16.3, 115.8)	0.008	40.2 (12.8, 74.3)	0.006	26.4 (−28.1, 122.5)	0.377
Suburb	0.13 (0.12, 0.15)	0.25 (0.15, 0.31)	0.35 (0.30, 0.39)	37.2 (−1.0, 90.0)	0.056	−1.0 (−49.0, 92.2)	0.973	45.4 (−8.7, 131.5)	0.104
Public transports									
All public transports combined	0.19 (0.16, 0.21)	0.11 (0.10, 0.12)	0.15 (0.13, 0.17)	86.6 (51.1, 130.3)	< 0.001	21.1 (−27.6, 102.3)	0.466	73.4 (29.4, 132.5)	< 0.001
Train	0.09 (0.07, 0.11)	0.07 (0.05, 0.08)	0.06 (0.05, 0.07)	193.7 (−3.8, 796.2)	0.057	27.6 (−38.0, 162.4)	0.470	128.6 (20.3, 334.2)	0.014
Tram/metro[b]	0.23 (0.18, 0.28)	0.27 (0.19, 0.33)	0.16 (0.14, 0.19)	52.7 (−2.5, 139.1)	0.064	27.7 (−55.5, 266.9)	0.641	49.5 (−37.7, 151.1)	0.073
Bus	0.21 (0.17, 0.24)	0.15 (0.14, 0.16)	0.20 (0.16, 0.24)	96.0 (52.2, 152.4)	< 0.001	−2.1 (−24.3, 26.5)	0.856	86.0 (4.1, 232.2)	0.038
Indoor									
Airport	0.51 (0.41, 0.59)	–	0.50 (0.41, 0.57)	83.8 (15.0, 193.9)	0.016	–	–	25.0 (−37.7, 151.1)	0.491
Train station	0.22 (0.17, 0.25)	0.25 (0.13, 0.33)	0.49 (0.21, 0.66)	103.6 (33.7, 210.0)	0.004	−11.8 (−68.3, 145.3)	0.790	29.4 (−43.3, 195.1)	0.503
Shopping centers	0.12 (0.11, 0.14)	0.17 (0.15, 0.19)	0.25 (0.17, 0.31)	66.9 (20.1, 132.0)	0.004	35.8 (−39.9, 207.0)	0.445	206.3 (−8.5, 924.7)	0.068
c) Mobile phone handset exposure									
Outdoor									
All areas combined	0.06 (0.05, 0.07)	0.06 (0.04, 0.08)	0.17 (0.05, 0.24)	52.6 (11.3, 109.2)	0.009	25.6 (−14.1, 83.9)	0.240	19.8 (−28.6, 100.8)	0.494
Central residential area	0.05 (0.04, 0.06)	0.04 (0.03, 0.04)	0.27 (0.00, 0.45)	132.5 (53.9, 251.2)	0.001	113.4 (11.2, 309.6)	0.027	−63.0 (−93.5, 111.0)	0.232
Non-central residential are[a]	0.02 (0.02, 0.03)	0.03 (0.02, 0.03)	0.04 (0.02, 0.05)	54.6 (−16.3, 185.7)	0.145	25.9 (−39.1, 160.4)	0.496	140.0 (32.5, 334.5)	0.008
Downtown	0.09 (0.07, 0.10)	0.11 (0.06, 0.14)	0.20 (0.16, 0.23)	45.4 (−15.3, 149.6)	0.154	40.6 (−49.2, 288.8)	0.473	−6.0 (−57.5, 108.1)	0.866
Suburb	0.06 (0.02, 0.08)	0.07 (0.00, 0.10)	0.15 (0.00, 0.22)	3.9 (−66.2, 219.3)	0.942	−34.0 (−75.2, 75.7)	0.367	146.3 (−2.1, 519.5)	0.054

Public transports									
All public transports combined	0.55 (0.33, 0.71)	0.70 (0.60, 0.80)	0.83 (0.70, 0.94)	8.4 (−38.8, 91.9)	0.783	22.1 (−43.1, 162.1)	0.608	24.0 (−37.7, 147.1)	0.540
Train	0.96 (0.44, 1.29)	0.83 (0.70, 0.93)	1.05 (0.88, 1.21)	−44.7 (−86.9, 133.3)	0.381	38.0 (−37.4, 204.0)	0.385	40.0 (−17.0, 136.3)	0.182
Tram/metro[b]	0.21 (0.10, 0.28)	0.41 (0.19, 0.55)	0.67 (0.50, 0.81)	53.5 (−40.8, 297.6)	0.367	−15.7 (−78.7, 234.6)	0.803	117.3 (10.6, 326.7)	0.028
Bus	0.27 (0.19, 0.34)	0.31 (0.13, 0.42)	0.30 (0.19, 0.38)	−4.3 (−64.0, 154.5)	0.929	228.2 (−14.5, 1159.4)	0.077	19.8 (−82.4, 717.7)	0.843
Indoor									
Airport	0.15 (0.12, 0.18)	–	0.17 (0.14, 0.19)	−19.8 (−55.5, 44.4)	0.422	–	–	−47.3 (−62.7, −25.5)	0.002
Train station	0.23 (0.14, 0.30)	0.17 (0.13, 0.20)	0.26 (0.12, 0.34)	72.9 (−61.1, 669.7)	0.433	5.6 (−50.6, 125.8)	0.876	359.2 (87.7, 1023.4)	0.004
Shopping centers	0.15 (0.09, 0.19)	0.23 (0.14, 0.30)	0.21 (0.13, 0.27)	128.8 (1.3, 416.7)	0.047	−1.0 (−60.4, 147.4)	0.982	1.9 (−54.8, 129.6)	0.963

[a] Annual changes refer to geometric mean due to the log-linear regression model.

[b] In Brussels, there are no trams, the corresponding measurements are performed in metros.

handset exposure reached statistical significance at only a few outdoor areas (central residential areas of Basel and Ghent as well as non-central residential area in Brussels) (Table 2c).

In public transports, RF-EMF exposure is highly variable as shown in Fig. 2a–c. Mobile phone handset exposure is the most relevant source in public transports, especially in trains. Total RF-EMFs tended to increase in most public transport settings but did not reach statistically significance for all public transports combined in any of the cities (Table 2a). Statistically significant trends for mobile phone handset exposure were only observed in metros in Brussels (117.3%, $p=0.028$) (Table 2c).

In indoor settings, total RF-EMF exposure increased significantly at the airport (64.3%, $p=0.032$) and shopping centers (100.7%, $p=0.005$) in Basel (Table 2a) but not at corresponding areas in Ghent and Brussels. Interestingly, across all indoor areas in all cities, mobile phone base station exposure showed a stronger temporal increase than mobile phone handset exposure (Table 2b and c). At the airport of Brussels even a significant decrease of handset exposure was observed (Table 2c).

4. Discussion

Our study offers a comparison and time trend analysis of RF-EMF exposure levels collected during one year in typical everyday microenvironments (outdoor areas, public transports and indoor settings) across three European cities. For outdoor areas we found a significant temporal increase of RF-EMF exposure levels. In public transports exposure levels were higher than in outdoor areas and showed a larger day to day variation and temporal increase did not reach statistical significance.

4.1. Interpretation

Overall, our study gives strong indications that, especially mobile phone base station exposure at outdoor areas increased over the study period between April 2011 and March 2012. At outdoor areas temporal increase was higher in Basel's area compared to that in Belgium. This may be due to the difference in increased coverage and capacity demands. A further explanation might be that the introduction of precautionary limits in Belgium, which came in effect in 2009 in Brussels (Ordinance of the Brussels Capital Region of 14 March 2007) and in 2011 in Ghent (Ordinance of the Flemish Region of Nov. 2010) and thus was still in the adaption process during the measurement period, could have slowed down the exposure increase, whereas precautionary limits in Switzerland were established since 2001 (ONIR, 1999).

Interestingly, highest exposure levels occurred consistently in trains across all cities with distinct contribution from mobile phone handsets. This has several reasons: the inner space of a train can be considered as a Faraday cage, reflecting emitted radiation by mobile phones. In addition, the density of people using their mobile phones is usually higher in trains than in other environments. Nowadays, mobile phones are not only used for messaging and calls anymore but rather also for using a large variety of web-based applications (apps), such as news alerts, e-mails, mobile television and many other apps, increasing the use of mobile phone handsets during train rides resulting in higher uplink exposure levels. Moreover, location updates or handovers are executed when moving around in order to maintain constant connectivity to the mobile phone base station of the respective area when the device is in stand-by mode or during a call, respectively (Urbinello and Röösli, 2013). These aspects are also relevant for the exposure situation in buses, trams and metros but in these environments we have mainly measured outside the

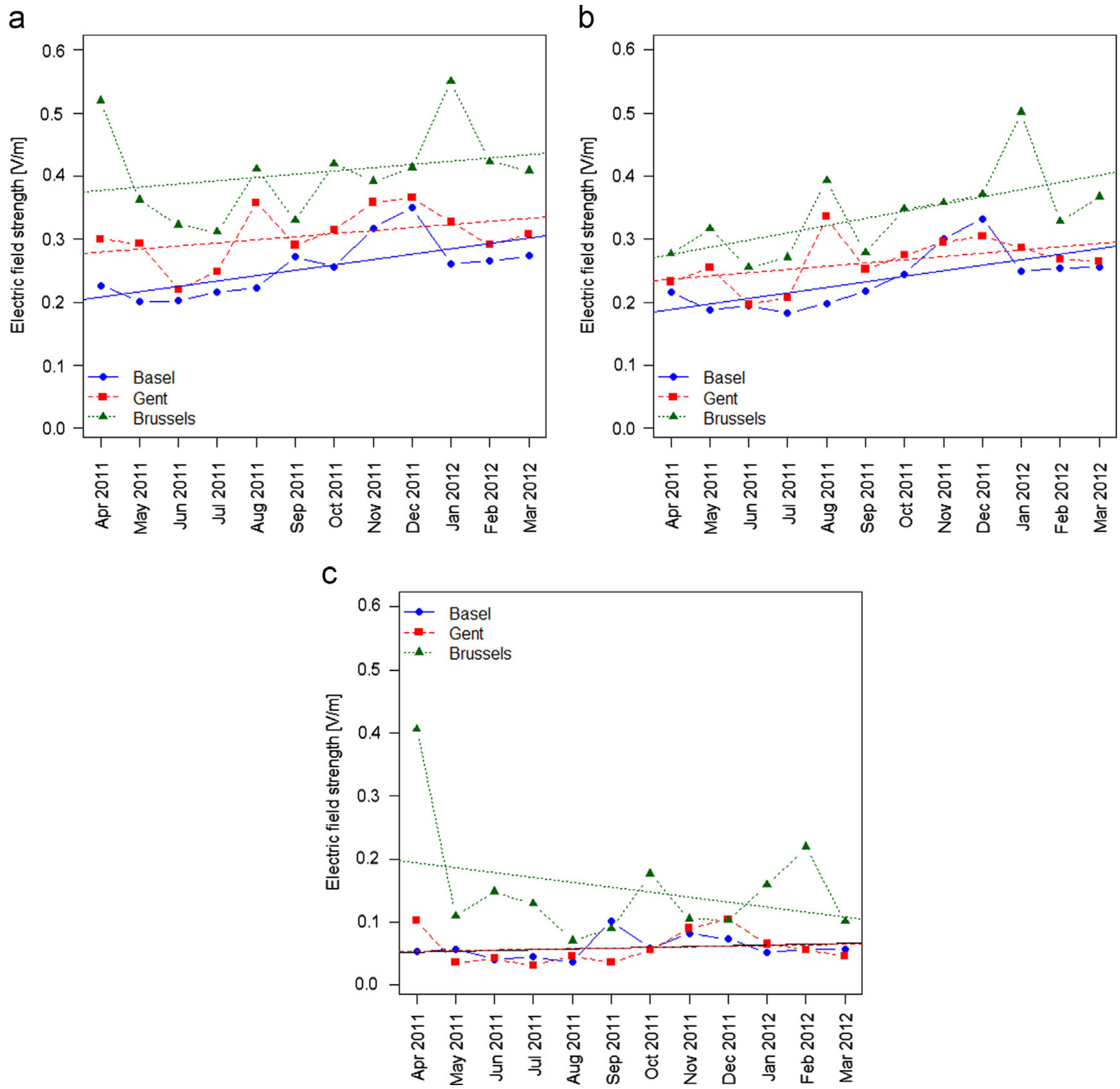

Fig. 1. Monthly average RF-EMF exposure levels for all outdoor areas combined between April 2011 and March 2012 for total RF-EMF (a), mobile phone base station (b) and mobile phone handset exposure (c).

commuting rush hours (Table 1) with a lower passenger density compared to trains.

The impact of the communication infrastructure on the exposure situation can be exemplarily highlighted by comparing measurements in trams and metros. Total mobile phone handset exposure was considerably higher in metros vs. trams (0.67 V/m vs. 0.21 and 0.41 in trams in Basel and Ghent), whereas mobile phone base station exposure was lower in metros than in trams (0.16 V/m vs. 0.23 and 0.27 V/m). Metros are running underground and in underground stations micro- and pico-cells are installed. Furthermore, the coverage in metros may be poor, so that the mobile devices have to emit with stronger signals.

We have hypothesized that increase of exposure levels would be most pronounced in public transports, because of the strong increase in internet use with mobile phones after the introduction of smart phones. However, this was not the case. Over all public transports combined, temporal trends did not reach statistical significance in all three cities. Lack of significance is partly explained by the higher data variability from handset exposure, which has resulted in larger confidence intervals. The lower increase on the relative scale is probably the consequence of higher exposure levels in public transports. Thus, the increase on the absolute scale is actually higher for many public transports compared to outdoor areas. For instance the observed (significant) 63.7% increase in geometric mean in the central residential area of Basel corresponds to an increase of 0.16 V/m whereas the (non-significant) 39% increase in trains in Brussels corresponds to 1.01 V/m. A further issue which may appear contradictory is the increase of exposure from mobile phone base stations and a decrease of exposure from mobile phone handsets at the airport since there is an interaction between up- and downlink exposure. However, this interaction is complex and it has been demonstrated that the higher are the exposure levels from the base station, the lower is the output power of mobile phones (Yuanyuan et al., 2014; Aerts et al., 2013). Further, one has to be aware that RF-EMF exposure decreases rapidly with increasing distance and thus, walking through a waiting hall at the airport will not capture uplink exposure from all emitting mobile devices in the considered area.

It is difficult to predict how RF-EMF exposure will further change over time. Assuming a linear trend of increase in RF-EMF exposure, it might be reasonable to argue that exposure will exceed regulatory limits somewhere in the future. However, along with the increase of new telecommunication devices, technologies became also more efficient in reducing emission characteristics of mobile phones. Our results suggest that the increase in number

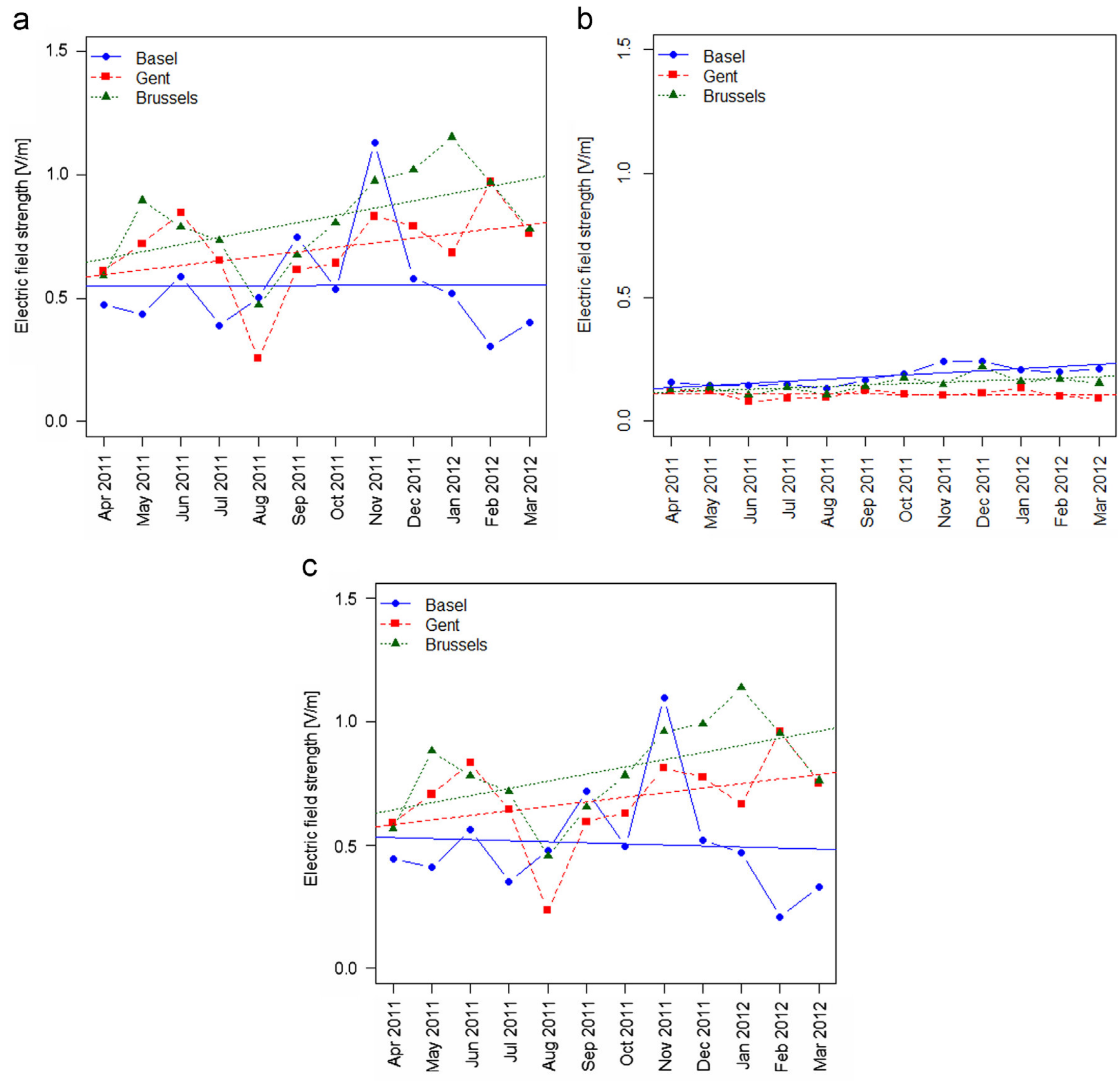

Fig. 2. Monthly average RF-EMF exposure levels for all public transports combined between April 2011 and March 2012 for total RF-EMF (a), mobile phone base station (b) and mobile phone handset exposure (c).

and amount of mobile phone users has not been compensated with more efficient technologies and the net effect is an increase in exposure levels for most microenvironments. Also the output power of mobile phones is affected by the technology. For example second generation mobile phones (2G, GSM) use a power control, radiating with full intensity during connection establishment and down-regulate as soon as a call has been established (Lönn et al., 2004). Smartphones of the third generation (3G, UMTS) in contrast, have a so-called enhanced adaptive power control which optimizes radiation according to the quality of connectivity to the mobile phone base station, resulting in considerable lower average output power (Gati et al., 2009; Persson et al., 2011; Wiart et al., 2000), which may also affect overall RF-EMF exposure.

4.2. Comparison of RF-EMF exposure levels with the literature

In previous studies, RF-EMF measurements had primarily been collected through volunteers, who filled in an activity diary and carried a measurement device during their typical daily activities. Since the volunteers were usually not asked to restrict their mobile phone use during the study (Frei et al., 2009), this affected personal measurements during a call (if not omitted from the data analysis) but also in stand-by mode because of organizational communication (Urbinello and Röösli, 2013), which could not be identified in the measurement file. If diary data were not entirely accurate in volunteer studies measurements might be assigned to the wrong microenvironment in such studies. Nevertheless, we found similar results in outdoor urban environments as in a previous study conducted by Joseph et al. (2010), which reported total RF-EMF exposure levels of 0.28 V/m for Switzerland (our study – Basel: 0.26 V/m) and 0.37 V/m for Belgium (our study – Ghent: 0.31 V/m, Brussels: 0.41 V/m). Exposure in trains were higher in our study (0.97 V/m in Basel, 0.83 V/m in Ghent and 1.06 V/m in Brussels) compared to the previous study: 0.63 V/m (Switzerland) and 0.59 V/m (Belgium).

In a recent study conducted by Bolte and Eikelboom (2012) in The Netherlands with 98 volunteers carrying a personal measurement device during their typical daily activities, similar total RF-EMF exposure values were reported for shopping centers (NL: 0.29 V/m vs. Basel: 0.22 V/m, Ghent: 0.32 V/m, Brussels: 0.37 V/m), outdoor areas (0.30 V/m compared to 0.26 V/m, 0.31 V/m and 0.41 V/m), railway stations (0.35 V/m vs. 0.34 V/m, 0.32 V/m and 0.57 V/m) and buses (0.29 V/m vs. 0.35 V/m, 0.36 V/m and 0.37 V/m). However, total RF-EMF exposure in trains was considerably lower in The Netherlands than in the present study (0.37 V/m vs. 0.97 V/m, 0.83 V/m and 1.06 V/m). In trams and metros, exposure levels were similar in The Netherlands (0.34 V/m) and in Basel (0.32 V/m) but higher in Ghent (0.50 V/m) and Brussels (0.70 V/m).

Note that all these previous studies included also DECT (Digital Enhanced Cordless Telecommunication) frequency when calculating total RF-EMF exposure, which is, not the case in our study. However, DECT cordless phone exposure is not expected to be relevant for RF-EMF exposure in outdoor and train environments, but rather more in environments like in households or in offices where people spend most of their time.

4.3. Comparison of temporal trends with the literature

The number of studies examining temporal trends based on personal measurements on a larger time scale up to one year is very limited. A study performed in Lower Austria examined spot measurements with a spectrum analyzer during daytime in bedrooms in 2006 and a follow-up investigation in 130 identical homes was performed in 2009 (Tomitsch and Dechant, 2012). The authors concluded from their results, that median RF-EMF exposure in bedrooms increased from 41.35 $\mu W/m^2$ (0.12 V/m) to 59.56 $\mu W/m^2$ (0.15 V/m). Median exposure from mobile phone base stations has increased by a factor 2 during these three years (from 7.68 to 15.12 $\mu W/m^2$). This study differed from our research in terms of microenvironments, as we did not measure in households, and the equipment (spectrum analyzer vs. exposimeter). In contrast a large survey of mobile phone base station measurements from the US, UK, Spain, Greece and Ireland did not indicate an increase in mobile phone downlink exposure between the years 2000 and 2009 (Rowley and Joyner 2012). The European narrowband measurements originated from monitoring sites close to mobile phone base stations on ground-base, whereas the US broadband measurements included many rooftops and other locations around base stations. The dataset of this publication is impressive but it is unclear whether temporal trends are affected by the underlying heterogeneous dataset, whereas our study used the exact same procedure over the entire study period. Monitoring systems have been implemented in various cities in Europe, such as in Greece (Gotsis et al., 2008), Italy (Troisi et al., 2008) and Portugal (Oliveira et al., 2007). However, no analyses of time trends are available from these measurement networks. In Basel, prior to this study, measurements have been already collected every month between May 2010 and 2011 in the very same microenvironments (Röösli et al., 2014). Time trend analyses for the entire 2-year period yielded annual increases ranging from 14% for downtown area up to 32% in central residential areas.

4.4. Strengths and limitations

A strength of the study is the use of a common measurement protocol in all three cities of Basel, Ghent, and Brussels. In previous studies, comparison of results between countries was limited due to different study designs: i.e. different applied methodologies, such as recruitment strategies of study participants, different data collection procedures and different methods of data analysis (Joseph et al., 2010). In the present study, the same study assistant collected measurements in all cities and performed all analyses ensuring accurate assignment measurements to microenvironment which might not be the case in the volunteer study. The mobile phone was switched off during data collection avoiding influences from the own mobile phone to personal measurements which could result in an overestimation of personal exposure, as it impacts personal measurements which were shown by Urbinello and Röösli (2013). In addition, the study design applying repetitive measurements on a monthly basis, at the same days and times, enabled to draw conclusions about temporal variations, for the first time during an entire year.

Our study also has limitations; since we just considered two working days and performed measurements during daytime, we have not taken into account temporal exposure trends during night or weekends. However, difference in exposure has been found to be low between different days of the week (Beekhuizen et al., 2013; Joseph and Verloock, 2010; Joseph et al., 2009). Exposure from mobile phone base stations seems to be slightly higher during weekdays than weekend (Joseph et al., 2009, Mahfouz et al., 2013) and electric field strength was found to be about 10–30% higher during daytime than during nighttime (Manassas et al., 2012, Mahfouz et al., 2011), indicating some overestimation of the average exposure situation.

Measurement duration in some of the microenvironments was relatively low (e.g. non-central residential area). This is not expected to bias the trend analysis, because this measurement protocol has been shown to provide reproducible values (Beekhuizen et al., 2013). However, the reported values may not be fully representative for the whole corresponding measurement area. The higher the spatial variability the less the representative values may be obtained with a short measurement duration. Thus, uplink exposure in all areas and downlink exposure in non-central residential areas with a low transmitter density are mostly affected. In order to address the representativity of our findings on a larger geographic scale we suggest applying our measurement protocol for at least 20 min or longer in additional microenvironments.

On the other hand, the exposimeter was carried close to the body in a bag, thus shielding of the human body is expected to have influenced our results to some extent, as shielding of the body is expected to lead to underestimation of personal RF-EMF exposure (Bolte et al., 2011; Iskra et al., 2010; Neubauer et al., 2010; Thielens et al., 2013). Resulting extent of underestimation depends on the frequency band. For the GSM900 downlink band correction factors between 1.1 and 1.3 and for UMTS downlink and W-LAN correction factors of 1.1–1.6 have been suggested (Bolte et al., 2011; Neubauer et al., 2010). Bolte et al. (2011) did a comprehensive uncertainty analysis for personal EME SPY 121 measurements addressing in addition to body shielding calibration and elevation arrival angle. To take all of these uncertainties in count, they propose frequency band specific correction factors between 1.1 and 1.6. Thus, the level of exposure may be somewhat underestimated; however, this bias is unlikely to have affected temporal trend analysis. We have only measured a limited number of microenvironments and thus, the generalizability of the observed trends in these microenvironments for all other environments from the same type in Belgium and Switzerland is somewhat uncertain. In terms of population exposure it would be interesting to extend this study to the work place and homes, where people spend most of their time. However, such a study would be very costly.

5. Conclusions

Our study offers for the first time a diligent comparison of temporal trends during a year between countries as it based on a common measurement protocol applied in all cities. We could consistently demonstrate that all exposure levels were far below reference levels proposed by ICNIRP (International Commission on Non-Ionizing Radiation Protection). Exposure levels were of the same order of magnitude in all cities. Consistently in all cities, exposure was highest in public transports (train) and lowest in residential areas (central and non-central residential areas). We found substantial increase of exposure levels for most microenvironments. It is crucial to further monitor the exposure situation in different environments in order to examine if and how exposure changes over time and to anticipate critical areas.

Conflict of interest

The authors declare no conflict of interest.

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.2014.07.003.

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ONLINE FIGURES

FIGURE 1. Paths along the different outdoor areas in the various cities.


Non-central residential area Basel
Peter-Ochs-Strasse
© 2009 GeoBasis-DE/BKG
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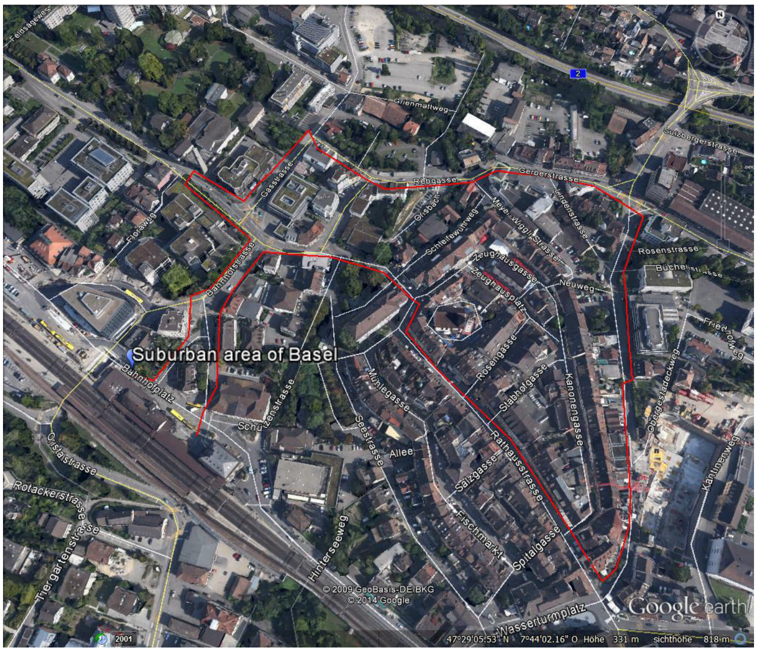
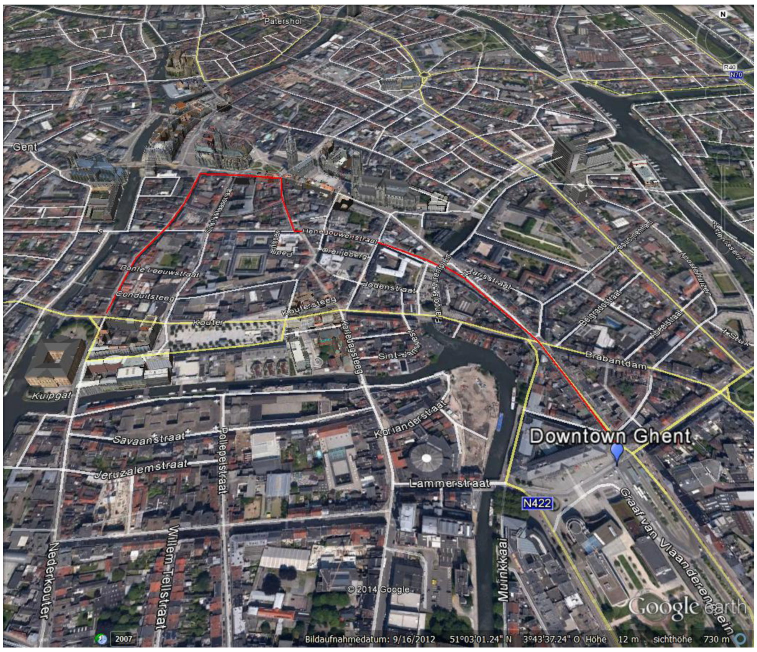
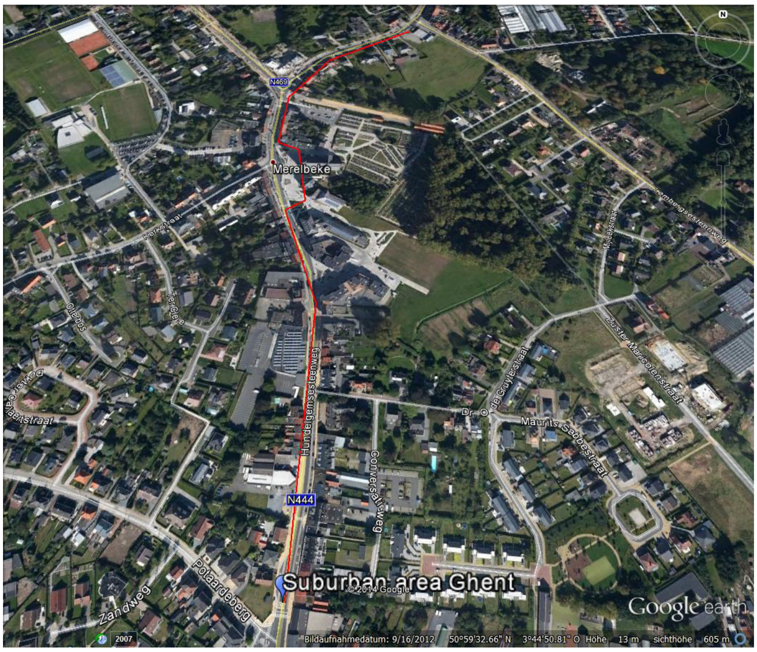
Google earth


Suburban area of Basel
Bahnhofplatz
Rosenstrasse
Kanonengasse
Rathausstrasse
Rebgasse
Allee
© 2009 GeoBasis-DE/BKG
© 2014 Google
Google earth


Central residential area Ghent
N414
R40
Tweekerkenstraat
Kunstlaan
Overpoortstraat
Kattenberg
Gaspar-de-Craeyestraat
Google earth
© 2014 Google


Downtown Ghent
N422
Brabantdam
Savaanstraat
Jeruzalemstraat
Lammerstraat
Kuipgat
Muinkkaai
Nederkouter
Willem-Tellstraat
Google earth
© 2014 Google


Non-central residential area Ghent
N414
N60
Galglaan
De Pintelaan
Google earth


Merelbeke
N444
Suburban area Ghent
Zandweg
Google earth


Central residential area Brussels
Duquesnoystraat
Violetstraat
Lombardstraat
Kaasmarkt
Grote Markt
Boterstraat
Beursstraat
Gasthuisstraat
Gerechtsplein
Kapellestraat
© 2014 Google
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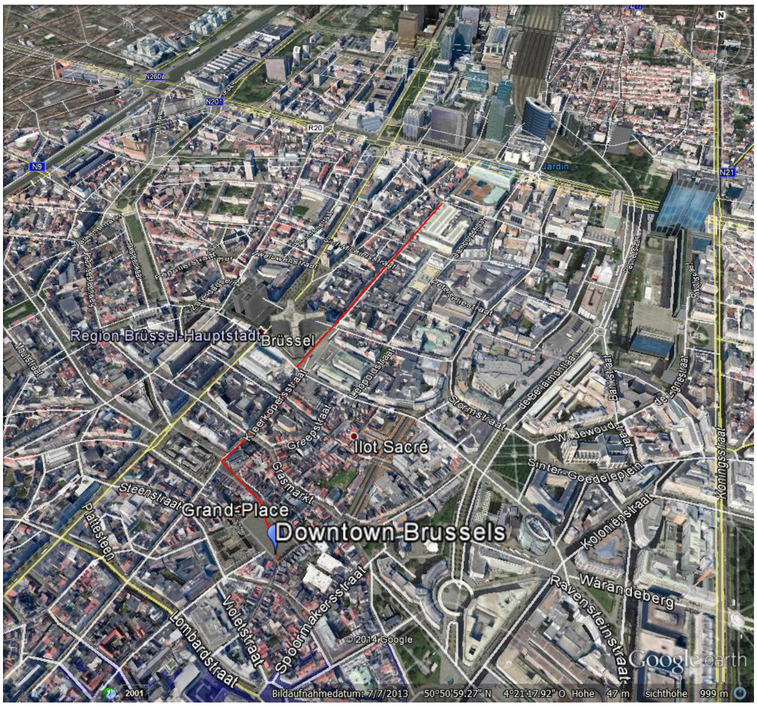
Downtown Brussels
Grand-Place
Ilot Sacré
Region Brüssel-Hauptstadt
Brüssel
Steenstraat
Violetstraat
Spoormakersstraat
Lombardstraat
Warandeberg
Ravensteinstraat
Koloniënstraat
Koningsstraat
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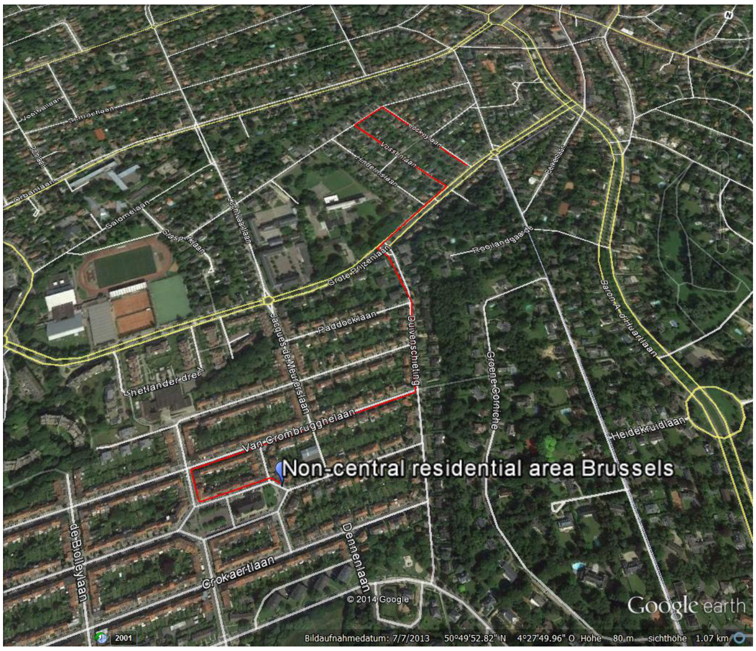
Non-central residential area Brussels
Van Grombrugghelaan
Crokaertlaan
Dennenlaan
Heidekruidlaan
© 2014 Google
Google earth


Suburban area Brussels
Stefaniastraat
Koningschapsstraat
Moorsledestraat
Emile Bockstaellaan
Ketelsstraat
© 2014 Google
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8 Summary of the main findings

In the subsequent Chapter, the main results of the different aims stated in the Chapter 2.2 are presented accordingly. Specific results can be found in the respective articles Chapters 4 to 7).

Objective 1: The effect of the own mobile phone on personal RF-EMF measurements.

The effect of location area updates when being in transit in public transports (public transports study) and during car rides (car study) was analyzed for different scenarios: (i) mobile phone turned off (reference), (ii) dual-band mobile phone (second generation) and a (iii) quad-band mobile phone (third generation) being in stand-by mode. Highest uplink (i.e. communication from the mobile phone to the mobile phone base station) exposure occurred in trains, reaching levels up to 0.67 V/m with lowest levels during car rides (0.02 V/m). Total uplink exposure (sum of GSM 900, GSM 1800 and UMTS uplink) originated mainly from the GSM frequency bands.

Public transports study: Total RF-EMF exposure for both public transports combined (train and bus), was 0.50 V/m for the reference scenario (mobile phone turned off), 0.40 V/m when having a dual-band mobile phone (second generation) in stand-by mode and 0.52 V/m for a quad-band mobile phone (third generation). The average proportion of uplink measurements in all transportation modes combined was up to 81.6% (reference scenario). GSM uplink measurements with an activated phone in public transports were of the same order of magnitude as the reference scenario. With a UMTS mobile phone, UMTS uplink levels were always higher compared to the scenarios with a GSM mobile phone and in the reference state.

Car study: Total RF-EMF exposure in all areas combined (rural, highway and urban) was 0.21 V/m for the reference scenario, 0.36 V/m for a GSM mobile phone and 0.78 V/m for a UMTS mobile phone in stand-by mode. Uplink measurements contributed up to 81.9% to total RF-EMF exposure. With activated mobile phones, measurements of the GSM uplink bands were substantially higher compared with the reference scenario. UMTS uplink levels increased for the scenario with a mobile phone of the third generation.

Objective 2: Reproducibility of personal RF-EMF measurements.

Reproducibility of mobile phone base station exposure measurements was investigated in Basel (Switzerland) and Amsterdam (the Netherlands) in different outdoor areas. Average mobile phone base station (downlink) exposure was highest in the downtown areas of both countries: 0.30 V/m in Basel and 0.53 V/m in Amsterdam. The lowest exposure was observed in residential areas: 0.09 V/m and 0.33 V/m. In all areas, the exposure was consistently higher in Amsterdam than in Basel. The contribution to total RF-EMF exposure consisted mainly by mobile phone base station radiation, especially from GSM frequency bands. Exposure from mobile phone handsets was considerably lower in outdoor areas. Exposure remained fairly constant during the measurement period of three months, but showed high fluctuations during daytime. Exposure levels showed a high spatial variability within outdoor urban areas. Nevertheless, day-to-day exposure was similar at different times of the day on the same location and measurement path, demonstrating a high reproducibility for mobile phone base station exposure. Analysis of variance (ANOVA) confirmed that sources of data variability were best explained by type of city (50%) and type of area (30%).

Objective 3: Influence of the mobile phone base station network on the exposure situation of the population.

To analyze the influence of precautionary limits on outdoor RF-EMF exposure levels and to characterize RF-EMF exposure in different outdoor areas, measurements were performed in Basel (Switzerland), Amsterdam (the Netherlands), Ghent and Brussels (Belgium). The average total RF-EMF exposure in all outdoor urban areas combined ranged between 0.25 V/m in Basel and 0.44 V/m in Brussels. Highest exposure levels were found in the downtown areas of the different cities: 0.32 V/m in Ghent, 0.34 and 0.49 V/m in Basel (based on two measurement paths in the downtown area of Basel), 0.57 V/m in Amsterdam and 0.58 V/m in Brussels. In contrast, lowest exposure levels occurred in non-central and central residential areas, varying between 0.16 V/m (Basel) and 0.42 V/m (Ghent). The most influential source in outdoor areas is attributed to mobile phone base stations (for all outdoor areas combined: 0.22 V/m (Basel) to 0.41 V/m (Amsterdam)). Exposure from mobile phone handsets was small, reaching exposure values of 0.06 V/m (Basel and Ghent) to 0.17 V/m (Brussels).

In terms of peak exposure levels for total RF-EMF exposure, values in central residential areas ranged between 0.27 V/m (99^{th} percentile: 0.45 V/m) in Basel and 0.73 V/m in Ghent (99^{th} percentile: 1.37 V/m), and in non-central residential areas the range was between 0.29 V/m (0.61 V/m) in Ghent and 0.73 V/m (1.13 V/m) in Amsterdam. Highest peak exposure levels occurred in the downtown area with levels of 0.52 V/m (Basel 2) and 0.94 V/m (Amsterdam) for the 95^{th} percentile and between 0.87 V/m (Ghent and Basel 2) and 2.08 V/m (Brussels) for the 99^{th} percentile.

Mobile phone base station exposure as a function of the corresponding regulatory limit for arithmetic means averaged over the entire study period showed that exposure levels in the central residential area of Ghent (0.36 V/m) and in the downtown area of Brussels (0.51 V/m) and Basel (0.47 V/m), with more stringent regulatory limits, were of similar magnitude as in Amsterdam (central residential area: 0.31 V/m; downtown: 0.51 V/m), which has the least stringent regulatory limits.

Objective 4: Characterization of RF-EMF exposure in everyday environments.

RF-EMF exposure levels were characterized in outdoor areas, public transports and indoor settings across several European cities. For all outdoor areas combined, average total RF-EMF exposure ranged between 0.25 V/m (Basel) and 0.44 V/m (Amsterdam). Highest exposure occurred in the downtown areas: 0.32 V/m (Ghent) to 0.58 V/m (Brussels). Whereas lowest levels occurred in residential areas (central and non-central residential areas) varying between 0.16 V/m (Basel) and 0.24 V/m (Brussels). Mobile phone base station exposure was the major source in outdoor areas causing mean RF-EMF levels between 0.22 V/m (Basel) and 0.41 V/m (Amsterdam) on the basis of all outdoor areas combined.

In all public transports combined, total RF-EMF exposure ranged between 0.59 V/m (Basel) and 0.84 V/m (Brussels), where highest exposure was measured in trains, reaching average levels up to 1.06 V/m (Brussels). Mobile phone handset exposure was the most relevant source in trains, contributing over 98% to total average RF-EMF exposure.

In indoor settings, typical average total RF-EMF exposure levels ranged between 0.22 V/m in shopping centers (Basel) and 0.57 V/m at the railway station (Brussels). Typical sources in indoor locations are primarily induced by mobile phone base stations (range: 0.12 V/m - 0.51 V/m) and mobile phone handsets (range: 0.15 V/m - 0.26 V/m) signals.

Objective 5: Temporal variation of RF-EMF exposure.

We investigated temporal variability of RF-EMF exposure in three European cities in outdoor areas, public transports and indoor settings. We observed a considerable change of the exposure situation during the period of one year between April 2011 and March 2012 across all cities.

Descriptive analysis suggested an increase of RF-EMF exposure in urban outdoor areas considering total RF-EMFs and mobile phone base station exposure which is the predominant source in outdoor areas. Trend analysis using multilevel mixed effects linear models indicated a highly statistically significant increase of mobile phone base station exposure for all outdoor areas combined in Basel (64.0%, $p<0.001$), Ghent (23.6%, $p=0.021$) and Brussels (68.3%, $p<0.001$). Area-specific yearly changes were most pronounced in Basel (range: 37.2% ($p=0.056$) in the suburban to 96.5% ($p=0.02$) in the non-central residential area) and Brussels (26.4% ($p=0.377$) in the downtown area to 120.2% ($p=0.002$) in the central residential area). In Ghent, annual changes of 40.2% ($p=0.006$) were observed in the downtown area. A considerable increase of 98.4% ($p=0.002$) and 120.2% ($p=0.002$) were observed in the non-central and central residential area of Brussels.

In public transports RF-EMF exposure was highly variable. Mobile phone handset exposure was the most relevant source in public transports, especially in trains. Significant increases of 117.3% ($p=0.028$) in annual exposure change in public transports were only detected in metros in Brussels. In Basel and Brussels, statistically significant yearly changes of mobile phone base station radiation (downlink) in all types of public transports have been found, increasing by 96% ($p<0.001$) in buses in Basel and by 128.6% ($p=0.014$) in trains and 86% ($p=0.038$) in buses in the city of Brussels. Surprisingly, exposure to mobile phone handsets in trains even seemed to decrease in Basel (44.7%, p=0.381), however without statistical evidence. In indoor settings, more variable RF-EMF exposure trends exist, with statistically significant increases for total RF-EMF exposure of 64.3% (p=0.032) at the airport, and 100.7% (p=0.005) in shopping centers in Basel; a similar phenomenon could be observed in Brussels, however, with lack of statistical evidence. Results indicate that mobile phone base station exposure consistently increased in all cities. Notably, a very large increase in mobile phone handset (uplink) radiation was observed at Brussels' railway station (359.2%, p=0.004), whereas at the airport, uplink radiation decreased by 47.3% (p=0.002).

9 Discussion

The discussion is structured according to the different objectives stated in Chapter 2.2. Specific findings are discussed in detail in the Articles 1 to 4 in the Chapters 4 to 7. In the Discussion, general aspects are presented focusing first on methodological aspects and expanding further to issue-specific aspects. The topics are put in context with the scientific literature and implications for future research are provided.

9.1 Methodological issues – draw the bow

Objective one addressed the question about the effect of the own mobile phone on personal RF-EMF measurements. We found that personal RF-EMF measurements are affected by one’s own mobile phone in stand-by mode. This is especially the case when driving around in a car compared to being in transit with public transports where results demonstrated a high background exposure influenced by other people’s mobile phone.

The introduction and development of new wireless telecommunication technologies and the substantial increase of environmental exposure to radiofrequency electromagnetic fields (RF-EMFs) in the last two decades has led to concerns in the general population about potential adverse health effects caused by RF-EMFs (Blettner et al., 2009; Neubauer et al., 2007; Röösli et al., 2010a; Röösli et al., 2010b; Schreier et al., 2006; Schröttner and Leitgeb, 2008). The World Health Organization (WHO) has identified the exposure assessment of RF-EMF levels for established and new RF technologies as well as the quantification of personal exposure from a range of RF sources and identification of determinants as a high research priority need (WHO, 2010).

RF-EMF exposure measurements are imperative for exposure assessments, including studies investigating potential adverse health effects of RF-EMFs.

The research conducted in the framework of this dissertation gives new insights in methodological approaches by taking into account several issues regarding personal mobile phone use, reproducibility of personal exposure measurements and the impact of the mobile phone base station network on population exposure to better understand and characterize RF-EMF exposure among the general population. We performed several monitoring studies in different everyday environments and across several European cities using personal exposimeters. A complete overview of the different measurement periods in the different cities and environments is illustrated in Figure 8 in the Methods section (Chapter 3.1).

9.2 The effect of the own mobile phone on personal RF-EMF measurements

Objective one addressed the question about the effect of one's own mobile phone on personal RF-EMF measurements. We found that personal RF-EMF measurements are affected by one's own mobile phone in stand-by mode. This is especially the case when travelling in a car compared to being in transit with public transports where results demonstrated a high background exposure influenced by other people's mobile phone.

Epidemiological studies using personal exposimeters have been recommended for RF-EMF exposure assessment (Ahlbom et al., 2008; Neubauer et al., 2007) and successfully applied in various recent studies (Bolte and Eikelboom, 2012; Frei et al., 2010; Joseph et al., 2010a; Röösli et al., 2010b; Thomas et al., 2008; Thuróczy et al., 2008; Viel et al., 2009). However, personal RF-EMF exposure in such studies was measured by recruited study participants who were allowed to use their own mobile phone (Frei et al., 2009a). When study participants carried around an exposimeter, their mobile phone was usually switched on, most of the time in stand-by mode. It is well-known that the own mobile phone affects personal measurements and this exposure source was neglected in previous studies. When looking at different exposure sources separately, neglecting the exposure of the own mobile phone can be a severe limitation, as the impact of the own mobile phone on uplink (i.e. communication from the mobile phone to the mobile phone base station) measurements can be considerable. A study conducted by Frei et al. (2009a) showed that mean RF-EMF uplink exposure levels of persons with a mobile phone during measurements were 0.13 V/m compared to 0.08 V/m for study participants without a mobile phone. We found that one's own mobile phone in stand-by mode has a substantial impact on personal RF-EMF exposure measurements in the three uplink frequency bands GSM 900 (Global System for Mobile Communications), GSM 1800, and UMTS (Universal Mobile Telecommunications System).

Along with the increase of new mobile devices, mobile phones became more sophisticated and efficient in reducing output power levels. As described in Chapter 1.4, dual-band mobile phones of the second generation (2G, GSM) radiate with full intensity during connection establishment of calls and down-regulate output power levels after connection has been established (Lönn et al., 2004). Newer mobile phones (smartphones), in contrast, use an enhanced adaptive power control (APC), adjusting output power according to the signal strength and connection quality (Gati et al., 2009; Kelsh et al., 2011; Persson et al., 2011; Wiart et al., 2000). So far, the impact of mobile phones in stand-by mode (without active calls) on personal measurements has not been investigated. We performed a study consisting of measurements conducted in public transports (train, tram, and bus) and during car rides in rural areas, on highways and in cities in Switzerland. Mobile phones have to communicate with the nearest mobile phone base station to provide information about the geographic position in order to maintain connectivity; this leads to constant uplink RF-EMF exposure when moving. Basically, it has to be differentiated between location area updates and handovers: (i) *location area updates* occur when traveling, and the mobile phone has to inform the cellular network about its position when changing the location area (Akyildiz et al., 1996; Lin et al., 2002); (ii) *handovers*, in contrast, take place when a mobile subscriber crosses the borders of a location area with an active call in progress, where an available channel must be assigned to the mobile phone in the destination cell to avoid termination of a call (Del Re et al., 1995). The performance of mobility management which allows tracking the location of mobile phones has a larger effect when being in transit, as being stationary with the mobile phone in stand-by mode. When travelling, subscribers repeatedly change the location area, which is covered by one or a group of mobile phone base stations, over time. The effect of location area updates on personal RF-EMF exposure measurements was investigated in our study (Article 1, Chapter 4). Our findings demonstrated that when travelling, location updates have a considerable impact on personal RF-EMF exposure. On the one hand the effect is triggered by regular location updates when changing the location area and on the other hand – which can be regarded as an additive effect – push notifications and updating of web-based applications trigger this effect. A recent study conducted by Mild et al. (2012) in Sweden investigated the effect of location updates of dual-band mobile phones (2G) in stand-by mode. They concluded that periodic location updates occurred once every two to five hours and that between these updates the mobile phone can be compared to a passive radio receiver without radiation (Mild et al., 2012). It has to be considered, however, that smartphones operating on four RF bands with web-based applications execute more updates and have distinct radiation characteristics when compared to mobile phones of the second generation (GSM) and thus communicate with higher periodicity with the nearest mobile phone base station. An important finding was that the personal uplink exposure during car rides can be reduced considerably, by orders of magnitude, by turning off the mobile phone and thus preventing location area updates. In this context it is of minor importance where the mobile phone in the car is placed. Our results showed that, even in a distant position to the source (e.g. back seat in the car), exposure is of the same order of magnitude as when the mobile phone is in closer proximity. When driving in rural areas, uplink exposure can be higher, because the network density is lower than in cities and the distance to the nearest mobile phone base station is generally larger. This in turn might result in higher output power levels. In urban areas, the exposure from the own mobile phone was slightly lower, but the influence of other people’s mobile phone walking on sidewalks had some influence in recorded uplink exposure levels, especially when waiting on traffic lights. In contrast, during tram, bus, and especially during train rides, background exposure from other people’s mobile phone was substantial, while the relative contribution of the personal mobile phone was small. We found that the own mobile phone operates to a greater extent on the GSM network than on UMTS frequency. This can be partly explained with the quantity and density of mobile phone base station networks, GSM and/or UMTS, in a specific area.

The impact of one’s own mobile phone on personal measurements leads to the question of whether call duration is an adequate exposure proxy, which has been considered as the most common exposure surrogate in RF-EMF research. As a consequence, future exposure assessment studies should not only take into account the call duration, but also exposure from mobile phones in stand-by mode when defining cumulative exposure as outcome. With the introduction of new mobile devices and with the dispersal of tablets, new RF-EMF emission characteristics occur and have to be taken into consideration. This might be of importance for studies with children and adolescents, as they start to use mobile devices early in life (Böhler and

Schüz, 2004; Söderqvist et al., 2007) and consequently cumulative lifetime exposure might increase.

9.3 Reproducibility of personal RF-EMF measurements

When planning exposure assessment studies based on personal measurements, a crucial question is how reproducible such measurements with personal exposimeters are. The second objective of this dissertation aimed to investigate how reproducible RF-EMF exposure measurements are and what potential sources may influence data variability. Therefore, we performed a monitoring study in different urban outdoor areas based on concurrently conducted measurements in two European cities, namely Basel (Switzerland) and Amsterdam (the Netherlands) to investigate this problem. Prior to addressing the question about the reproducibility of personal exposimeter measurements, advantages and disadvantages of different exposure assessment methods will be discussed (confer also Chapter 1.6).

Comparison of different exposure assessment methods

In Chapter 1.6, the most common exposure assessment methods are presented (Figure 5). In the current Chapter, different measurement devices are discussed based on the results, declaring strengths and limitations.

Broadband probes are mainly used to identify maxima and allow a fast-scanning of the environment, but are not suitable for identifying exposure of specific sources due to technical restrictions. We performed some measurements in Ghent and Brussels using broadband probes at pre-defined locations to identify average exposure prior to measure accurately with a spectrum analyzer.

Narrowband measurements using *spectrum analyzers* and broadband probes have been described in several studies (Joseph et al., 2010b; Joseph et al., 2012; Joseph et al., 2006; Schmid et al., 2007; Siran and Seyhan, 2009; Tomitsch et al., 2010; Verloock et al., 2010) and are used for fixed-site monitoring. They allow very accurate measurements also differentiating between different providers with a measurement uncertainty of ± 3 dB (CENELEC, 2008; Joseph et al., 2012). However, they require technical skills from trained personnel and are cost- as well as resource-intensive (Bornkessel et al., 2010; Joseph et al., 2009). Moreover, the spectrum analyzer settings have a huge impact on measurement results (Joseph et al., 2012;

Verloock et al., 2010). Standard procedures for in-situ measurements of electromagnetic field strength are described in Joseph et al. (2009) and CENELEC (2008). Comparison between measurements with an exposimeter of the type EME Spy 140 and a spectrum analyzer data was performed at three different time instances (between September 2011 and May 2012) in Ghent and Belgium (data not shown in this thesis). The spectrum analyzer was placed on a fixed site in free space and the exposimeter on the ground. The ratio between the spectrum analyzer (SA) and exposimeter (Exp) (E_{SA}/E_{Exp}) varied between 1.12 and 4.32 considering the 3 time instances, indicating poor agreement between the two devices.
Mobile monitoring with portable *exposimeters* is a suitable approach when targeting to get a general impression of the RF-EMF exposure and to differentiate between sources. The usefulness of personal exposimeters along with research recommendations including their limitations have been discussed in several studies (Ahlbom et al., 2008; Mann et al., 2005; Neubauer et al., 2007; Radon et al., 2006; Röösli et al., 2010b). The advantage of exposimeters is that they allow collecting a large amount of data in various environments with relatively little effort (Röösli et al., 2010b). Their manageable size of around 19 cm allows the subject to carry them around, for example in a bag. Two examples of commercially available exposimeters are the EME Spy 120 and its successor EME Spy 140 (SATIMO, Courtaboeuf, France, http://www.satimo.fr/) which measure isotropic (in all directions) and are able to quantify exposure in 12 and 14 different frequency bands, respectively. The position of the exposimeter is an influential factor when collecting data. When carrying the exposimeter on the body, shielding effects, due to interactions of the human body with RF-EMFs, may lead to underestimation of the exposure (Iskra et al., 2010; Neubauer et al., 2008). Shielding of the body can have variable effects on measured exposure if wearing the exposimeter close to the body (Bolte et al., 2011; Knafl et al., 2008; Neubauer et al., 2008). Studies performed by Iskra and colleagues showed through models that exposure can be underestimated up to 6.5 dB (Iskra et al., 2010; Iskra et al., 2011). In a study by Bolte et al. (2011), they found that exposimeters tend to underestimate the true exposure according to tests in a gigahertz transverse electromagnetic cell and by controlled measurements at an open area test site wearing one or two exposimeters. Blas et al. (2007) showed that uncertainty can even reach 30 dB for single point measurements due to reflection of EMFs of the body (Blas et al, 2007). We compared how mean mobile phone base

station exposure values differed between measurements taken with an exposimeter placed near the body in a bag and distant to the body in a pushchair cart (1 m distance to the body and around 1 m height above ground) in outdoor areas. Ratio of the power flux density (S) averaged over the entire study period ($S_{distant}/S_{proximal}$) varied between 0.24 and 1.05 in outdoor areas. It happened that the exposimeter in the bag (proximal) measured even higher values as the exposimeter placed distant from the body. Nevertheless, further studies should be performed to further investigate this issue. The effect of the main beam direction of the antenna, building characteristics in the area-specific environments, position and orientation of the exposimeter and environmental conditions (water, snow) are important factors influencing measurements. Exposimeters are not very accurate when measuring RF-EMF exposure from near-field sources since measured exposure strongly depends on the distance to the source. In consideration of all factors influencing exposure, the best method would be to keep the exposimeter distant from the body preventing body shielding effects. Nevertheless, we found that if carrying the exposimeter in a bag, measurements are reliable and consistent allowing characterizing far-field exposure levels in different environments.

Optimal conditions to measure RF-EMF exposure hardly exist, and a certain level of uncertainty has to be taken into account. Nevertheless, the measurements have to be easy to manage when data collection is intended to carried out repeatedly over a long time. Exposimeters are also suitable for personal exposure assessments through study participants. Exposimeters are recommended when the purpose of the study is to get a general impression of the RF-EMF exposure situation and its distribution among various sources in different environments. If performing repeated measurements, one main aspect is how reproducible such exposimeter measurements are. This will be discussed in the following section.

How consistent are personal measurements in terms of reproducibility and what are influencing factors?

As suggested by a study of Bornkessel et al. (2007) determining the general public exposure around GSM and UMTS base stations, it is not recommended to measure only at one fixed position as this is not representative for the mean or maximum exposure. Concurrently conducted measurements in Basel and Amsterdam had been performed using personal exposimeters to address the question of reproducibility.

We measured exposure dynamically by walking along pre-defined measurement paths in different outdoor urban areas (Article 2, Chapter 5) with a bicycle trailer (Amsterdam) and a pushchair cart (Basel) placing the exposimeter distant from the body.

We found RF-EMF exposure to be spatially highly variable, differing considerably in urban outdoor areas. This was consistently observed for all measurements conducted in the framework of this thesis (Article 2 to 4, Chapters 5 to 7). For example, comparing mobile phone base station exposure in two areas of the city of Basel, a central residential (denoted as Area 3 in Figure 11) and downtown area (denoted as Area 4), mean exposure values were 0.12 V/m and 0.30 V/m, respectively, despite their proximity to one another (Figure 11). The same spatial variability has been found in Amsterdam, Ghent and Brussels (Chapters 6 and 7). An important determinant influencing spatial RF-EMF variability is the density of mobile phone base stations in the different outdoor urban areas. It clearly comes across that exposure levels in the downtown area are higher due to a denser cellular network where, in addition to mobile phone base stations, micro-, pico- and femto-cells are installed. The spatial distribution of RF-EMF exposure patterns will be further elaborated in Chapter 9.6.

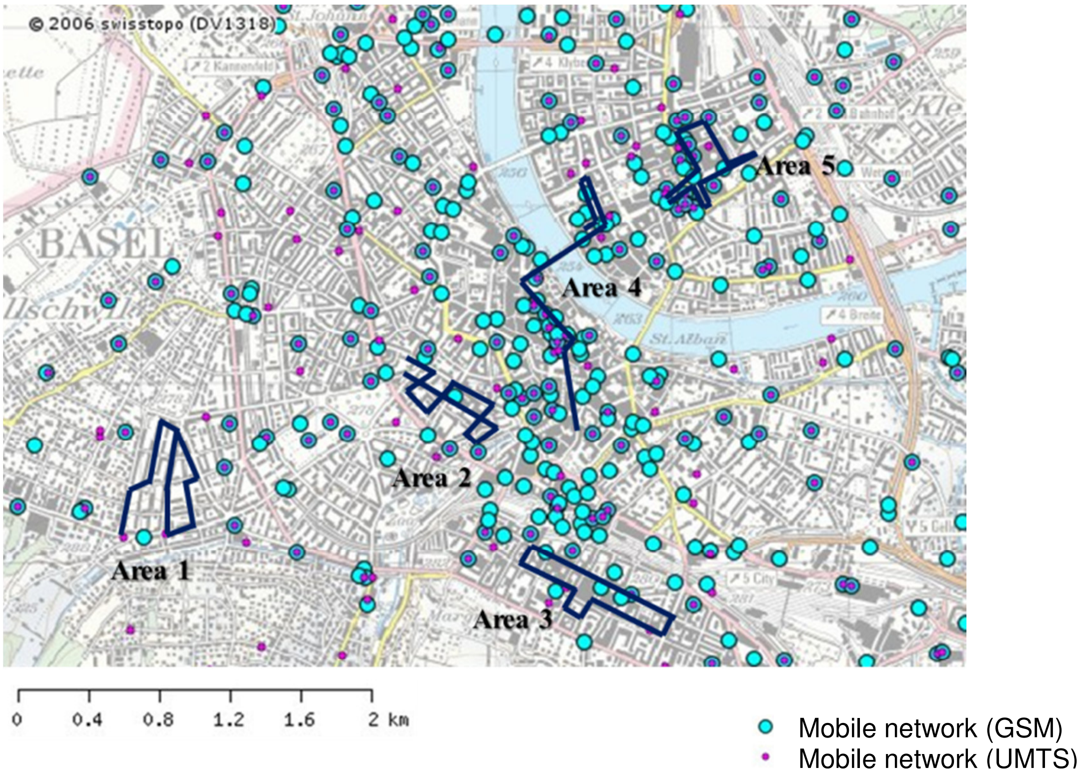

Figure 11: Measurement paths and mobile phone base station density of GSM and UMTS towers.

Despite the high spatial and temporal RF-EMF variability from mobile phone base stations (Frei et al., 2009b), it turned out that mobile phone base station (downlink) exposure measured with personal exposimeters was highly reproducible when performing repeated measurements along the same measurement paths at different times of the day (morning, noon, afternoon). Measurements were conducted during three months (November 2010 to January 2011). However, the repeatability of mobile phone base station exposure on the same route could also be confirmed when expanding the study period to ten months (Beekhuizen et al., 2013). We found that the high spatial variability in our study in different outdoor areas was best described by type of area (30%) and type of city (50%), according to analysis of variance (ANOVA) models (Chapter 5). A study of Frei et al. (2009a) examining exposure levels in a sample of volunteers living in Switzerland found that weekly exposure measurements were reproducible when they repeated measurements in a sub-sample (32 participants) of the study population consisting of 166 volunteers.

The choice of the measurement path is a crucial point when planning an exposure assessment study and characterizing outdoor RF-EMF exposure levels as it largely influences measurements. It would be recommendable to include different measurement routes in the same study area, depending on the size and mobile phone base station density of the area, to better describe RF-EMF exposure variability and situation. Interestingly, average mobile phone base station exposure remained fairly constant during the study period of three months when measuring along the same path at different times, despite the daily fluctuation of RF-EMFs. Variability over longer time periods (over three months) is discussed in Chapter 9.7.

The issue of reproducibility of personal RF-EMF measurements is of crucial importance, in order to have reliable measurements enabling a consistent comparison over time. If comparing exposure levels between cities, it is fundamental to determine areas based on matching criteria like building height, proximity to main roads and traffic, pedestrian zones, and green space in order to equalize as much as possible. For the downtown area we have chosen a typical meeting point in the city center, central residential areas are characterized in terms of pedestrian activity and higher building heights up to 4 to 5 floors compared to lower building heights in non-central residential areas (2 to 3 floors) in quiet areas with green space. A further possibility is to define or categorize areas according to the population density per square kilometer.

9.4 Influence of the mobile phone base station network on the exposure situation of the population

The precautionary principle

With the ongoing development and enduring introduction of new telecommunication technologies (Webb, 2007), concerns regarding potential adverse health effects are prevalent in the population, and there is an uncertainty about long-term health effects of continuous low exposure levels. Polls have shown that persons are more concerned about potential adverse health effects from fixed site transmitters, i.e. mobile phone base stations, than from sources that they use personally, such as mobile devices (Schreier et al., 2006). The International Commission on Non-Ionizing Radiation protection (ICNIRP) recommended frequency-specific reference levels (see Chapter 1.3) which are 42 V/m for GSM 900, 58 V/m for GSM 1800 and 61 V/m for UMTS. Below these ICNIRP reference levels, no health effects could consistently be demonstrated (ICNIRP, 1998; Röösli et al., 2010a). Following concerns in the general population, several countries adopted a precautionary principle lowering their standard limits at so-called sensitive places where people spend most of their time (see Chapter 1.3). We addressed the question if and how regulatory exposure limits affect the RF-EMF exposure situation in outdoor urban areas (objective 3). Therefore, we performed measurements in different residential (central and non-central) and downtown areas across the cities of Basel, Ghent and Brussels, where precautionary limits are imposed, and Amsterdam, where ICNIRP levels are valid (Article 3). Table 3 gives an overview on the different frequency-dependent regulatory limits imposed in the different cities.

Our results demonstrate that all RF-EMF exposure levels were far below the ICNIRP reference levels. Minimizing exposure to RF-EMFs was recommended (Berg-Beckhoff et al., 2009; Blettner et al., 2008; Neubauer et al., 2007; WHO, 2010) and, accordingly, precautionary limits were adopted by several countries at national and even at regional level, as in Belgium (different limits for Ghent and Brussels, Table 3).

Frequency	Basel[1]	Ghent[2]	Brussels[3]	Amsterdam[4]
900 MHz	4 V/m	3 V/m	2.9 V/m	41 V/m
1800 MHz	6 V/m	4.2 V/m	4.1 V/m	58 V/m
2100 MHz	6 V/m	4.5 V/m	4.3 V/m	61 V/m

Table 3: Overview of the regional directives for different cities.

[1]Regulatory exposure limit per base station for sensitive areas: living rooms, school rooms, kindergarten, hospitals, nursing homes, places of employment, children's and school playgrounds.

[2]Regulatory exposure limit per antenna: valid for indoor places and children's playgrounds.

These regulatory limits are estimated by calculating $0.1 * \sqrt{f}$ (with *f* as the frequency in Hz) for the frequency range between 400 MHz and 2 GHz and 4.48 V/m for 2 GHz to 10 GHz.

GHz. There is also a limit for cumulative exposure of 21 V/m (at 900 MHz, frequency dependent).

[3]Regulatory exposure limit for cumulative RF-EMF exposure: valid at all public availability places (exceptions for various technologies).

[4]Regulatory exposure limit for cumulative RF-EMF exposure.

The effect of precautionary limits on the exposure situation of the population is difficult to analyze, as it is influenced by many different factors such as comparability of areas included in the study, exposure assessment methodology and many more. The initial hypothesis was that lowering regulatory limits may affect in turn the configuration of the mobile phone network, since when lowering the output power of mobile phone base stations to decrease exposure, more base stations are required to compensate the reduction. This could potentially result in higher RF-EMF exposure. We did not find indications that lowering regulatory exposure limits resulted in increased mobile phone base station exposure levels. Area-specific comparisons showed similar mobile phone base station exposure levels between Amsterdam and other cities. Interestingly, peak exposure levels (95th and 99th percentile) sustain the fact that they are not related to the level of the regulatory limit.

Comparing exposure levels across different cities or countries, as was done in the framework of this thesis (Chapters 5 to 7), requests a certain degree of comparability in order to have reliable results which can be cross-compared between countries or cities (Joseph et al., 2010a). In all studies where we characterized outdoor urban exposure we matched areas as accurately as possible based on several criteria, previously described in Chapter 9.3. In addition, we developed a common measurement protocol using uniform data collection and data analyses procedures. This was done for concurrently conducted measurements in Basel and Amsterdam as well as for a multi-center study in Basel, Ghent and Brussels. As described in the previous Chapter, the measurement path is a crucial issue when planning an exposure assessment study with the aim to characterize outdoor urban RF-EMF exposure levels. The path determines, to a large extent, measured RF-EMF exposure which may be responsible for unintentionally higher values. Thus, line-of-sight (LOS) and non-line-of-sight (NLOS) conditions should be taken into account, which will be further explained in Chapter 9.6. There are indications that in LOS conditions, the field strengths are generally higher than in NLOS conditions (Kühn, 2009). Mobile phone base station density is also an influential factor to be considered. In a denser network, tilts and mast height may be lower whereas in rural or non-central residential areas, exposure levels may increase since the mobile phone has to radiate with higher output power to communicate with the mobile phone base station; this was further issued in Article 1 (Chapter 4).

Three cities have adopted precautionary limits which are approximately 10 times lower than ICNIRP reference levels and in one city, ICNIRP levels are imposed without precautionary limits. It would be important to consider different cities with different limits between the clusters of Brussels, Ghent, Basel and, on the other end, Amsterdam, in future studies.

Reference values are related to maximal values at hotspots over time. Exposimeter measurements rather represent average exposure values. Consequently, mean values calculated based on data collected with a personal exposimeter do not demonstrate that reference values are met at each point in time and space. RF-EMF patterns are very heterogeneous, both in outdoor areas and indoor locations (Bornkessel et al., 2007).

Implications

The precautionary principle is controversially discussed resulting in political implications including several initiatives at local, regional, and national levels with the aim to inhibit the mobile phone base stations sprawl. One could argue that the level of RF-EMF exposure in the population is not relevant as long as the reference levels are not exceeded. Furthermore, social aspects regarding concerns of the population act as a strong influence on the implementation of the precautionary principle. According to a study by Vecchia (2007), undermining credibility of science-based guidelines by social considerations, such as public anxiety, should be avoided. Leitgeb (2008) concluded that implementation of the precautionary principle should not be triggered by uncertainty and not be misinterpreted as a definite risk. A recently published study by Wiedemann et al. (2013) examined the effects of precautionary information on risk perception, focusing on mobile telephony. Interestingly, they concluded that informing people about precautionary measures does not result in decreased public concerns (Wiedemann et al., 2013). However, in the light of current uncertainties it may be justified to minimize exposure as much as possible. Our study provides at least some evidence that the introduction of precautionary limits does not unintentionally increase the mean RF-EMF exposure of the population. Any risk should be reduced if this is easily and economically achievable (Leitgeb, 2008). Therefore, it is of great importance to study temporal changes of RF-EMFs, especially as new technology standards are being introduced – such as UMTS (Universal Mobile Telecommunication System) – or are in the phase of implementation, such as LTE (Long-term Evolution) in order to evaluate and adapt current policies regarding RF-EMFs. The pronounced spatial and temporal variability of RF-EMFs illuminates the difficulty in predicting long-term developments of RF-EMFs.

9.5 Issue-specific perspectives

Understanding the spatial and temporal variation of RF-EMF exposure patterns, elucidates the complex dynamic of radiofrequency electromagnetic fields (RF-EMFs) in our everyday environment and, thus, gives a better understanding on how to plan future epidemiological studies in RF-EMF research. After the description of methodological challenges, the following two Chapters aim to characterize RF-EMF exposure in different typical environments and to investigate the temporal variability of RF-EMF exposure.

9.6 Characterization of RF-EMF exposure levels in everyday environments

Spatial distribution

Very little is known about RF-EMF exposure in everyday life as personal exposimeters became available only a few years ago (Joseph et al., 2010a). In addition, the continuous introduction of new mobile technologies alters the exposure situation. Objective four of this thesis addressed the characterization of RF-EMF exposure levels from various sources in typical everyday environments, such as various outdoor areas, different public transportations, and several indoor settings. Exposure levels measured in Basel were placed in an international context with three European cities: Amsterdam (only outdoor measurements), Ghent and Brussels. The cross-comparison of RF-EMF exposure levels across countries was limited in previous studies due to differences in methodology regarding the data collection procedure or the data analysis (Joseph et al., 2010a). This was the first study to assess RF-EMF exposure in typical everyday environments using a unique study design in all cities with a common data collection procedure protocol and uniform data analysis.

Characterizing RF-EMF sources in everyday environments

The main contribution to the total RF-EMF exposure was predominantly influenced by telecommunication technologies from mobile phone handsets (uplink) and mobile phone base stations (downlink) contributing between 77.1% and 99% to total RF-EMF exposure, depending on environment (outdoor area, public transports or indoor setting). The radiation in outdoor areas was mainly influenced by mobile phone base stations. We found relative contributions of 87.4% (Basel), 87.5% (Ghent) and 61.9% (Brussels) of downlink exposure on total RF-EMF exposure. In public transports, the dominant source was uplink exposure, contributing 87.5% (Basel), 96.1% (Ghent) and 95.8% (Brussels) to total RF-EMF exposure. In indoor settings, both, uplink and downlink exposure were the main sources contributing between 14.6% (Basel) and 23.9% (Brussels) for uplink exposure and between 64.5% (Brussels) and 79.0% (Basel), respectively. An international study comparing RF-EMF exposure in different urban areas across Europe (Belgium, Switzerland, Slovenia, Hungary, and the Netherlands) by Joseph et al. (2010a) found similar results. In their study, exposure in transportation vehicles ranged between 92.5% and 96.6% in trains. In outdoor urban areas, contribution from downlink sources accounted for over 80% in Belgium, around 40% in Switzerland and 70% in the Netherlands, whereas in Slovenia it contributed only to approximately 20%. We conclude that telecommunication technologies are the most influential sources of the total RF-EMF exposure arising mainly from mobile phone base stations and mobile phone handsets.

The exposure distribution of spatial RF-EMFs is complex, because of a large variety of sources with different radiation characteristics contributing differently to everyday RF-EMF exposure. Mobile phone base stations produce very variable exposure patterns (Bornkessel et al., 2007) as has been indicated in the previous Chapters of the Discussion. It has been shown that the distance to the mobile phone base station is not the only influencing factor, but orientation to the main lobe and the sight conditions have a greater impact on RF-EMF exposure (Bornkessel et al., 2007). Regarding the sight, it can be differentiated between line-of-sight (LOS) which is a propagation of electromagnetic waves without obstacles between transmitter and receiver and non-line-of-sight (NLOS) which represents a class of propagation where a multipath propagation leads to interference by obstacles between transmitter and receiver and, thus, only scattered waves arrive at the terminal (Ferrara et al., 2007). Our findings are in line with previously conducted epidemiological studies, demonstrating that RF-EMF exposure levels vary considerably in different outdoor locations within one urban area as presented and described in the studies of Bornkessel et al. (2007), Frei et al. (2009a), Frei et al. (2010), Frei et al. (2009b). Figure 12 exemplifies the variation of the exposure within an area: the simulation illustrates the electric field strength distribution from radiation of two mobile phone base stations with nine antennas on the top of a building along a street in a residential area in the city of Brussels, taking into account spatial features: information about the position, the form, and the height of the buildings in the target area.

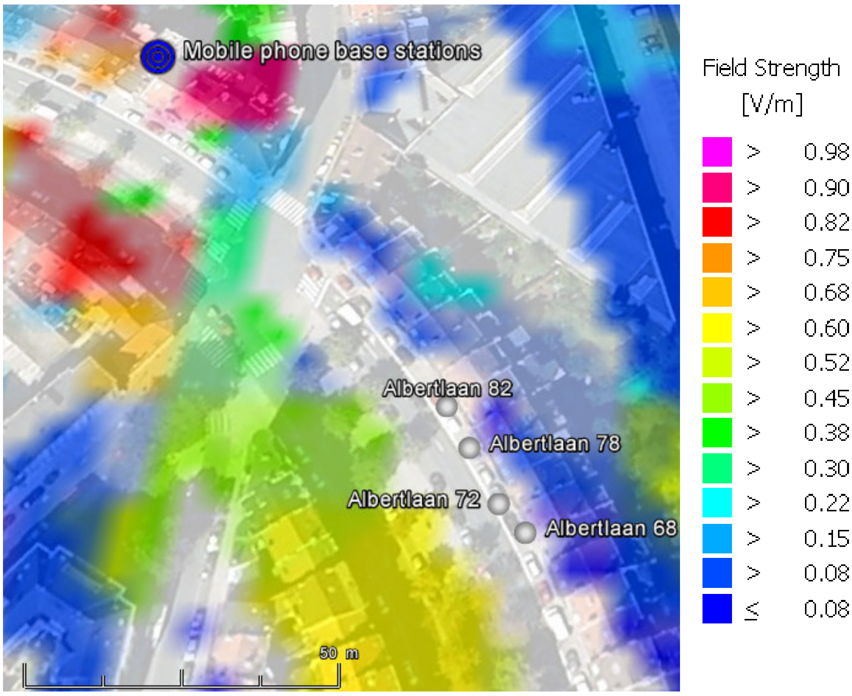

Figure 12: Propagation model of the electric field strength for a selected street in line-of-sight with a mobile phone base station in a residential area of Brussels (calculated using WinProp Software Package v12, AWE Communications, Gaertringen, Germany).

For mobile phone base station exposure, many factors are influencing exposure patterns: building characteristics, tilts of the antennas, mast heights, type of environment (rural, central), the whole topology of an environment, such as density of buildings, height and geometry of buildings, the density of mobile phone base stations in an area and if they are in LOS or NLOS condition to the measurement device, and climatic effects, such as rain or snow, may also influence EMFs. All these factors strikingly complicate measurement accuracy.

RF-EMF exposure levels in everyday environments

Detailed results are presented in Articles 3 and 4 (Chapters 6 and 7). Our results showed that highest exposure levels in outdoor urban areas occurred consistently in the downtown areas of each city, with typical total RF-EMF (all frequencies combined except DECT) exposure values ranging from 0.32 V/m in Ghent to 0.58 V/m in Brussels. In other areas such as urban residential areas, exposure levels were between 0.16 V/m (Basel) and 0.42 V/m (Ghent). The most important sources in outdoor areas are mobile phone base stations. The spatial variation can partly be explained by the mobile phone base station density in the respective areas, with a higher base station density in downtown areas, including also micro- and pico-cells, as in residential areas (Chapter 9.3, Figure 11). However, with a denser mobile phone base station network, the output power of mobile phone base stations might be lower and, thus, average exposure levels might even increase; though this did not occur according to our results presented in Article 3 (Chapter 6). In public transports, highest total RF-EMF values have been measured in trains with average levels between 0.83 V/m in Ghent and 1.06 V/m in Brussels, reaching peak exposure levels in terms of the 99th percentile of up to 3 V/m (Brussels). The high RF-EMF exposure levels in trains have several implications: the inner space of a train can be considered as Faraday cage, reflecting emitted radiation by mobile phones. Additionally, the number of people using their mobile phones' is usually higher in trains than in other environments. The main source of total mean RF-EMF exposure in public transports, especially in trains, is mobile phone handset radiation. We observed a widespread use of mobile phones during train rides. Nowadays, mobile phones are not only used for messaging and calls but they are rather offering a large variety of web-based applications (apps) such as newspapers, e-mail programs, mobile television, radio, and many others. This leads to an increased use of mobile phone devices during train rides resulting in higher uplink exposure levels. Moreover, location updates or handovers are executed when moving around in order to maintain constant connectivity to the mobile phone base station of the respective location area when the device is in stand-by mode or during a call (Chapter 4 and 9.2). Both mobile phone handsets as well as mobile phone base stations are important sources in indoor settings such as shopping centers, airports, and railway stations. Typical total average RF-EMF exposure levels in indoor settings ranged between 0.22 V/m (shopping centers in Basel) and 0.57 V/m (railway station in Brussels). We did not perform studies in residential homes where DECT has been found to be the most important contributor accounting for over 50% of exposure in Swiss urban homes (Joseph et al., 2010a). Interestingly, exposure levels in outdoor areas, public transports, and indoor settings were of the same order of magnitude across all cities (Basel, Ghent and Brussels) with same exposure patterns regarding total RF-EMF and mobile phone base station exposure.

Several studies were performed in different countries assessing RF-EMF exposure levels (Bolte and Eikelboom, 2012; Frei et al., 2009a; Joseph et al., 2010a; Viel et al., 2009). A comparison between the different findings of several studies is illustrated in Figure 13. A study conducted by Frei et al. (2009a) in the framework of the Qualifex (Health related quality of life) study found similar total RF-EMF exposure values of 0.28 V/m in outdoor areas (our study: 0.26 V/m), 0.29 V/m in shopping centers (0.22 V/m), 0.66 V/m in trains (0.97 V/m) and 0.53 V/m at the airport (0.54 V/m). We found also similar results in outdoor urban environments as in a previous international comparison study conducted by Joseph et al. (2010a). Exposure in trains was lower compared to our study. There are some differences between the studies of Joseph et al. (2010a) and Frei et al. (2009a) compared to our study. Firstly, they included also DECT frequency when calculating total RF-EMF exposure and secondly, data collection was (partly) performed through recruited study participants who were partly allowed to use their mobile phone during measurements which may have resulted in higher uplink exposure levels. However, results were in the same order of magnitude considering outdoor areas but higher in trains. This can be explained on the one hand with the increasing use of mobile phones nowadays and on the other hand with the resulting increased number of location updates and/or handovers while travelling in trains. In a recent study by Bolte and Eikelboom (2012), personal RF-EMFs 24h-measurements of study participants in the Netherlands have been conducted examining exposure levels and variability for everyday activities. Total RF EMF levels in the Netherlands (including DECT) were in the same order of magnitude in shopping centers, outdoor areas, at the railway station and in buses. In contrast, total mean RF-EMF exposure in trains was considerably lower in the Netherlands than in Switzerland. In trams and metros, results were comparable in the Netherlands and in Basel but higher in Ghent and Brussels. Figure 13 gives an overview of the different average total RF-EMF exposure levels in the different environments between the different studies. Cross-compared, exposure levels and patterns were fairly similar across the different studies and countries.

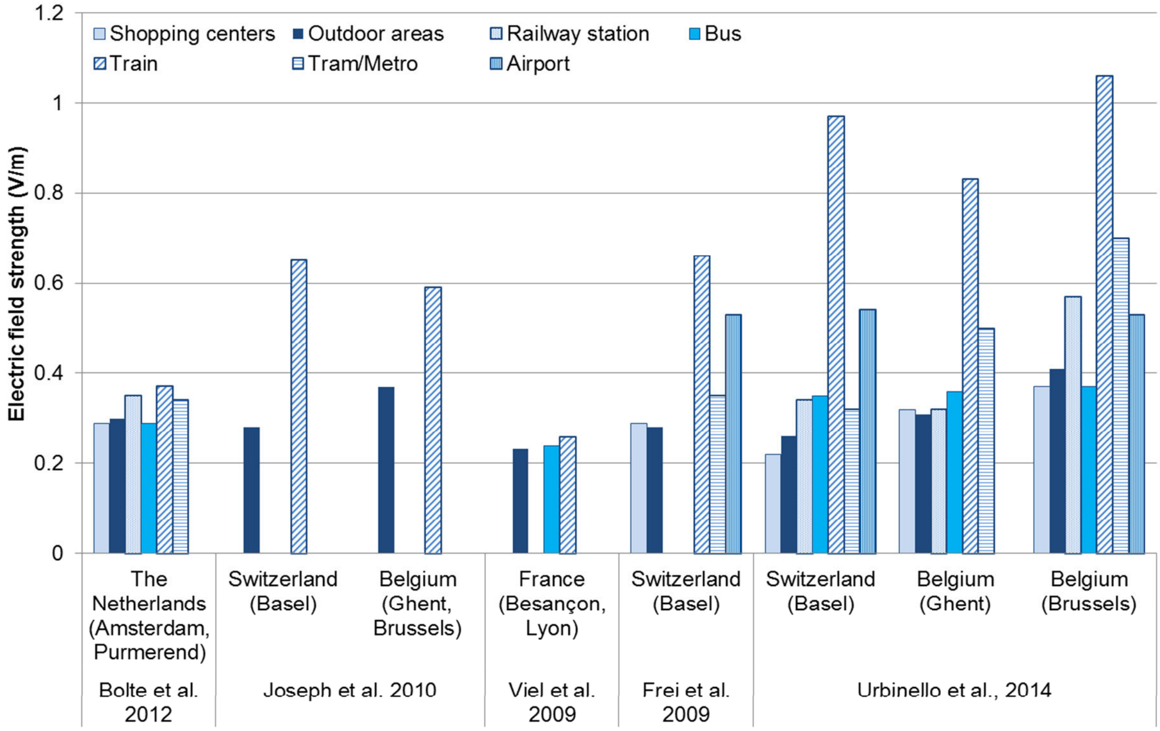

Figure 13: Comparison of the different average total RF-EMF exposure levels in different environments across several European countries by study.

Near-field and far-field sources

Near-field sources such as mobile phone handsets or cordless phones produce locally higher exposure values than far-field sources like broadcast transmitters and mobile phone base stations. The energy from a mobile phone near the head is around 1'000 to 100'000 times higher compared to exposure from a far-field source (Lauer et al., 2013). However, exposure from near-field sources, for example during a call, is typically of short duration where the head is the most exposed part of the body. Exposure from far-field sources is, in contrast, continuous where the whole body is exposed. Furthermore, exposure decreases drastically with increasing distance to a source (confer Chapter 1.2). Doubling the distance will result in around half of the exposure. In order to examine the cumulative exposure from far-field sources compared to near-field sources, the Qualifex study was conducted between April 2007 and February 2008 where 166 study participants carried around an exposimeter (Frei et al., 2009a). Exposure from far-field sources was on average 0.21 V/m. Based on our measurements, conducted in Basel, exposure from far-field sources was somewhat higher, ranging between 0.31 V/m in outdoor areas and

0.41 V/m in indoor settings. However, we considered also mobile phone handsets as a far-field source, since the mobile phone of the person performing measurements was turned off which may partially explain our higher exposure levels. In addition, we observed an increase in RF-EMF exposure levels in different everyday environments which is further elaborated in Chapter 9.7. In addition, the mobile phone use of 1,300 study participants was investigated in the framework of the Qualifex study. The average call duration per week of study participants was 62 minutes. Based on dosimetric models, the absorbed energy caused by dual-band (2G) and quad-band mobile phones (3G, smartphones) was calculated for specific organs and the whole body. As described in Chapter 1.2, technologies differ in their output power levels. GSM mobile phones have higher transmission powers by a factor of 100 to 1'000, while smartphones adapt their output power levels according to the network quality and signal strength (Gati et al., 2009; Kelsh et al., 2011; Persson et al., 2011; Wiart et al., 2000). This becomes relevant when moving around, as we found that the impact of one's own mobile phone is considerable even when the mobile phone is in stand-by mode (Chapter 4). This is particularly important for smartphones due to more frequent communications with the mobile phone base station because of applications requiring regular updates (e.g. push notifications of e-mails, breaking news and other web-based applications). Table 4 compares the energy absorbed for second and third generation mobile phones and for far-field sources which highlights the 200-fold difference of the energy absorbed by the brain between GSM and UMTS mobile phones.

Organ	Second generation phone user	Third generation phone user	Far-field sources	Proportion of far-field source for 2G usage	Proportion of far-field source for 3G usage
Whole body	111 mJ/kg	0.7 mJ/kg	35 mJ/kg	20.2%	55.8%
Brain (grey substance)	1002 mJ/kg	5 mJ/kg	42 mJ/kg	3.4%	17.2%

Table 4: Comparison of the cumulative exposure dose (absorbed energy) during 24 hours for near-field and far-field sources at average far-field exposure (Lauer et al., 2013).

9.7 Temporal variability

RF-EMFs are not only highly variable in space but also in time. Objective five investigated how RF-EMFs varied over time. Examining temporal variability of RF-EMF exposure, we observed an increase in various microenvironments over the study period between April 2011 and March 2012 based on multilevel mixed-effects linear models which were calculated on power flux density levels and then back-transformed to electric field strength. Especially mobile phone base station exposure in outdoor areas increased. Increases were more pronounced in Basel than in Belgian cities which might be explained by a different coverage and capacity demands. Furthermore, a slowed introduction of UMTS technology in Belgium could have contributed to a delayed 3G coverage. The introduction of precautionary limits in Brussels (Ordinance of the Brussels Capital Region of 14 March 2007) in 2009 and in Ghent (Ordinance of the Flemish Region of November 2010) in 2011 could have slowed down the exposure increase, where precautionary limits in Switzerland are imposed since 2001 (ONIR, 1999). Our results give indication that the increase in number and amount of mobile phone users has not been compensated with more efficient technologies. As described in Chapter 1.4, second generation mobile phones radiate with full intensity during connection establishment and down-regulate when connected (Lönn et al., 2004). Third generation smartphones, in contrast, use an enhanced adaptive power control which optimizes output power according to the quality of connectivity to the network, resulting in substantially lower average output power levels (Gati et al., 2009; Persson et al., 2011; Wiart et al., 2000), which may also impact RF-EMF exposure. Our initial hypothesis was that increase of exposure levels would be highest in public transports, due to a strong increase of mobile phone usage, the Faraday cage effect and because density of people using their mobile phones' is higher than in other environments. However, temporal trends did not reach statistical significance in all three cities, even if – interestingly – highest exposure levels occurred consistently in trains. Lack of statistical significance resulted in the higher data variability from mobile phone handset exposure, and thus causing larger confidence intervals.

The increase on the absolute scale is higher for many public transports compared to outdoor areas; e.g.:

An observed significant increase of 63.7% in geometric mean in the central residential area of Basel corresponds to an increase of 0.16 V/m. In contrast, a non-significant increase of 39% in trains in Brussels results in an increase of 1.01 V/m.
To date, studies investigating temporal trends based on personal measurements on a larger time scale up to several months or years are limited.
Monitoring systems have been implemented in different European cities, such as Greece (Gotsis et al., 2008), Italy (Troisi et al., 2008) and Portugal (Oliveira et al., 2007). However, no time trends analyses are available from these networks. A large survey of mobile phone base station measurements from the US, UK, Spain, Greece and Ireland showed no increase in downlink exposure between 2000 and 2009 (Rowley and Joyner, 2012). The European narrowband measurements differed from the US broadband measurements, since European data originated from ground-base and US data from roof-top measurements. In this context, it is not clear whether temporal trends are affected by this heterogeneity of data. An Austrian study from Tomitsch and Dechant (2012) examined spot measurements with a spectrum analyzer in bedrooms in 2006 and a follow-up was conducted in 130 identical homes in 2009. Median RF-EMF exposure in bedrooms increased from 41.35 µW/m^2 (0.12 V/m) to 59.56 µW/m^2 (0.15 V/m) and a two-fold increase in RF-EMF downlink exposure was observed, from 7.68 (0.05 V/m) to 15.12 µW/m^2 (0.08 V/m). Nevertheless, this study differed in terms of equipment (we used exposimeter) and microenvironments (we did not measure in households) to our study. Frei et al. (2009a) stated that introduction of mobile phone technology has resulted in a 10-fold increase of RF-EMF at outdoor areas compared to the time period before when broadcast transmitting was the most relevant source.
Different studies analyzed temporal variability during shorter time periods, as during 24 hours (Bolte and Eikelboom, 2012; Mahfouz et al., 2011; Mahfouz et al., 2013; Manassas et al., 2012; Miclaus et al., 2013), or during several days (Joseph and Verloock, 2010; Joseph et al., 2009; Vermeeren et al., 2013), up to several weeks (Beekhuizen et al., 2013). Studies investigating RF-EMF exposure variability during 24 hours concluded that traffic fluctuations cause considerably variable fields of GSM and UMTS exposure over one day, whereas variability was lower during night than during daytime (Joseph and Verloock, 2010; Mahfouz et al., 2011; Manassas et al., 2012). Bolte and Eikelboom (2012) analyzed exposure of 98 volunteers in or around Amsterdam investigating differences between daytime, evening and night-time.

During daytime exposure was about the same, but during night it was about half, and in the evening it was about twice as high. Joseph and Verloock (2010) characterized temporal variations during one week, accounting for 7.5 dB variations regarding GSM and UMTS signals. Signals of TRX (transceiver channels, i.e. GSM traffic channels) varied substantially reaching ratios up to 41.5 dB. Manassas et al. (2012) described diurnal variations of EMFs due to broadcast transmitters and mobile phone base stations. Results indicated median variations of 20.2% and 33.8% for broadcast and telecommunication signals. Vermeeren et al. (2013) investigated spatial and temporal RF-EMF exposure in 55 different indoor microenvironments, such as schools, crèches, homes, and offices in Belgium and Greece with spectral equipment and with personal exposimeters during one week. They found variations to be of the same order of magnitude as results presented by Manassas et al. (2012), reaching on average for total exposures up to 40% in crèches (Belgium) and 58% in homes (Greece). Frei et al. (2009a) and Viel et al. (2009) examined differences in RF-EMF exposure levels between work-days and weekends, finding similar exposure values and thus showing no larger differences across days of the week. We cannot exclude, based on our results, that there might be deviances between work-days and weekends as well as differences between daytime and night-time. Our measurements had been conducted exclusively during daytime at work-days, mainly on Wednesdays and Thursdays. Expanding the time period to several weeks, as presented in Article 2 (Chapter 5), we found that average mobile phone base station exposure in different outdoor areas remained fairly constant during three months and daily variability was large (Beekhuizen et al., 2013). To the best of my knowledge investigation of long-term RF-EMF exposure variability during several months has never been assessed so far and our study was the first addressing this issue (Chapter 7).

Prediction of RF-EMF exposure is challenging because of its large spatial and temporal variability and due to small and large-scale variations as a result of power control of mobile phone base stations. The mobile telecommunication system responds dynamically. The simple assumption: the more mobile phone base stations or mobile phone handsets, the higher the exposure levels, is not applicable. The installed transmission power of mobile phone base stations in an area is of limited representativeness for the exposure of the population. The distance to the mobile phone base stations, or microcells in downtown areas, is also a decisive criterion, as well as the distance to the main lobe (Bornkessel et al., 2007). In addition, quality of connectivity and density of mobile phone base stations have an effect on the power control of mobile phone handsets and mobile phone base stations. In general, one can say that the better the connectivity, the lower the output power for the communication. The introduction of precautionary limits may decelerate increases of RF-EMF exposure levels. However, as previously described in Chapter 9.4, our results did not sustain the hypothesis that precautionary limits may decrease peak exposure levels. But they neither do unintentionally increase average mobile phone base station exposure. It is desirable to minimize the total RF-EMF exposure of the population as much as possible since long-term effects of low-dose exposure are fraught of uncertainty. This applies to both the exposure to mobile phone base stations as well as mobile phone handsets. Currently, with the introduction of new technology standards such as LTE (Long-term Evolution), monitoring of the exposure is of great importance, as the mobile phone base station network becomes denser, and, according to the data of the International Telecommunication Union (ITU), the numbers of mobile-cellular subscribers is steadily increasing. In this context, the issue arises that assuming a linear trend in RF-EMF exposure, exposure will exceed precautionary limits somewhere in the future. However, along with the increase of new telecommunication devices, technologies became also more efficient in reducing output power levels and with a denser mobile phone base station network, output power of antennas may be reduced. Based on our findings, the relative increase in exposure levels results in a small absolute increase of electric field strength so far.

9.8 Strengths and limitations

Strengths

This thesis offers for the first time a standardized comparison of RF-EMF exposure levels with a common study design across several European cities. Measurements were performed based on a common measurement procedure in various environments (outdoor, public transports and indoor) at pre-defined times and measurement days of the week. To ensure comparability across cities, data analysis was conducted by the same person applying the same analysis procedures for all datasets. Previous attempts to compare results based on extracted data from different studies where different data collection or analysis methods had been applied (Joseph et al., 2010a).

Personal RF-EMF measurements were conducted personally, having the mobile phone turned off during measurements allowing reliable source allocation and attributing uplink exposure to mobile phone exposure to people around. Measurements during calls with mobile phones or DECT phones strongly depend on the distance between the device and the exposimeter (Frei et al., 2009a). Since exposimeters cannot realistically reflect exposure from near-field sources close to the body (Inyang et al., 2008), we considered the exclusion of the personal mobile phone as a strength for source allocation.

In some cases, more than 80% of data were censored and results are tenuous (Helsel, 2005). To account for the large proportion of measurement points under the lower detection limit of the device (censored values or nondetects), as often occurred, we applied the robust regression on order (ROS) algorithm to get more reliable results (Röösli et al., 2008). If less than three measurements were above the detection limit for a given area and frequency band, the arithmetic mean value was set to a virtual detection limit of 0.000265 mW/m^2 (0.01 V/m). Summary statistics calculated with robust ROS are more reliable as when using the naïve approach by simply calculating average levels, since they are more resistant to non-normality errors.

Limitations

The effect of body shielding can lead to a notable underestimation of RF-EMF exposure. In the majority of our measurements, only one exposimeter was carried around in a bag on the rear of the body.

In one city (Amsterdam) the exposimeter was not of the same type (EME Spy 140) and had different detection limits (EME Spy 120: 0.05 V/m vs. EME Spy 140: 0.001-0.005 V/m, depending on the frequency) and is able to measure on more frequencies (EME Spy 140 quantifies additionally WiMax (Worldwide Interoperability for Microwave Access): 3400 to 3800 MHz and W-LAN 5G: 5150 to 5850 MHz). To obtain comparable results, we censored the Amsterdam data at the same detection limit as the data collected with the EME Spy 120 at 0.05 V/m and excluded the two additional frequency bands (WiMax and WiFi 5G). Furthermore, we checked if

summary statistics differed depending on the censoring of the data on EME Spy 140 or EME Spy 120 level but found no differences.
As discussed in Chapter 1.5, measurement paths determine, to a large extent, exposure levels. Thus, data has to be interpreted with caution in terms of the general exposure in the different cities. To get a better impression of the exposure situation of an area, different paths within an area should be defined and measured.
When examining the impact of regulatory limits on mobile phone base station exposure in outdoor areas, results have to be interpreted carefully, since only four cities were included; with three cities having implemented precautionary limits and one city having adopted the ICNIRP levels (Table 3, Chapter 9.4).
Our measurements were performed only during working days: Wednesdays and Thursdays. There might be differences between working days and weekends as well as between daytime and night-time. Differences have been found to be low at different days of the week according to different published studies discussed in Chapter 9.7.
A further effect we observed is out-of-band response of the EME Spy 120. In order to check measurement consistency, calibrations of the EME Spy 120 exposimeter were performed at the Laboratory for Electromagnetic Fields and Microwave Electronics of the Swiss Federal Institute of Technology (ETH). Calibration factors showed out-of-band response indicating that DECT measurements were affected by the presence of GSM 1800 downlink and UMTS uplink exposure. However, DECT is not a relevant source in outdoor areas or public transports and may play only a role in indoor settings, such as train stations or airports.

9.9 Public Health relevance

Monitoring the RF-EMF exposure situation of the general public is imperative and also stated as high research priority in the Research Agenda of the World Health Organization (WHO, 2010). There has been a resilient increase in mobile telecommunication technologies with a durable introduction of new devices in the last twenty years. The number of mobile phone subscriptions in Switzerland registered 1’133 customers in 1978 and increased to 10’082’636 by the end of 2011 (OFCOM, 2011). With this development, the mobile phone base station network had to be and is still being expanded resulting in a higher density of the network along with new technology standards. Mobile telecommunication is pervasive worldwide nowadays, not only in developed but also in developing countries where, as shown in Figure 4, a strong increase in mobile telephony has been observed. Thus, even if there is a small risk, this would have severe public health consequences due to widespread use of mobile telecommunication services.

Especially with the introduction of newly developed mobile devices such as smartphones and tablets, the exposure profile from near-field sources has markedly changed, as these devices are also capable of running web-based functions and applications. This might lead to higher exposure levels from the mobile phone handset due to the more frequent communication with the nearest mobile phone base station. New exposure proxies should be considered to approximate the influence of the own mobile phone when performing web-based updates and/or for locating updates when moving around. The difference between dual-band (2G) and quad-band (3G) mobile phones has been drawn up in the Chapter 1.4 showing that output power regulation of smartphones is different from dual-band mobile phones. The exposure contribution of a mobile device in stand-by mode or when connected to the internet needs further clarification as this is now more relevant with mobile devices using web-based applications.

Accordingly, exposure of the general public considerably changed over the last two decades (Frei et al., 2009a; Neubauer et al., 2007; Röösli et al., 2010b). There are still knowledge gaps in EMF research, and the question of potential health implications continually leads to political debates. The research on biological and health effects of non-ionizing radiation is a tedious issue where quick and easy answers do not exist, as the subject is too complex. People are still concerned about potential adverse health effects (Frei et al., 2009a; Röösli et al., 2010a; Schreier et al., 2006; Wiedemann et al., 2013) of EMF due to uncertainty and lack of understanding about involved biological mechanisms. It has consistently been observed in all studies conducted in the framework of this thesis as well as in previously conducted studies that RF-EMF exposure is far below the ICNIRP (International Commission on Non-Ionizing Radiation Protection) reference levels (Frei et al., 2009a; Joseph et al., 2010a) where no health consequences have been proved unambiguously. Regarding non-thermal effects caused by RF-EMF, there are still many open questions and knowledge is thin (Hug and Röösli, 2013). Long-term observations are lacking, and it is not possible to draw any conclusions about potential long-term risks. Subsequently, minimizing exposure is recommended (Hug and Röösli, 2013). We could demonstrate to a certain extent that lowering regulatory limits does not unintentionally lead to an increased exposure situation as one might think. For example, lowering the output power of mobile phone base stations has to be compensated with lower masts or with the introduction of more base stations or microcells. Nevertheless, in the shadow of knowledge, further long-term studies evaluating the impact of regulatory limits on exposure situation of the general public are urgently needed.

Our study gives some indications for persons who want to minimize their personal exposure. Uplink exposure from the own mobile phone can considerably be reduced by up to a factor of 100 by turning off the mobile phone while driving in a car. In public transports, it is difficult to reduce personal exposure as it has been found that background exposure arising from other people's mobile phone is very high, especially in trains, whereby the relative contribution of the own mobile phone to the personal exposure is minor. Further recommendations provided by governmental agencies, such as the WHO or federal offices, suggest the use of headsets when calling, minimizing call duration, or to use alternatives like text messages. Furthermore, they advise to turn off WLAN if not needed. Exposure from mobile phones in stand-by mode can be reduced by omitting the configuration of regular updates for push notifications as e-mails or other web-based functions. Furthermore, when buying a mobile phone, one can consider devices with low SAR (Specific Absorption Rate, see Chapter 1.1) values. If possible, calls should be made when the signal strength is good, minimizing output power of the mobile phone. Finally, keeping distance to mobile devices or WLAN routers helps to minimize personal RF-EMF exposure.

9.10 Outlook

The path to unlimited communication is paved. A world without mobile telephony is inconceivable nowadays. The more it is important to monitor the exposure of the population as also stated in the Research Agenda of the World Health Organization (WHO). Studies exploring RF-EMF exposure levels and temporal trends are needed to better understand the dynamics of EMF.

We observed a transitional phase in terms of an increase and expansion of wireless mobile technology. Public transports are going to implement free WLAN and to equip trains with repeaters (to strengthen the outgoing signal of mobile phone handsets). In an advertisement from the Swiss Federal Railways (SBB) in November 2013, they currently plan to offer free WLAN in the 100 largest railway stations within the next two years (www.sbb.ch/wifi, accessed on 17.11.2013). In addition, some larger cities in Switzerland are in progress of offering free public WLAN. In the framework of this dissertation, the emphasis was put on telecommunication technologies examining RF-EMF exposure mainly from mobile phones and mobile phone base stations as these are the most relevant sources in everyday environments. Reasoning that wireless internet is a source of growing importance, future exposure assessment studies should also consider frequencies for mobile internet such as WiMax (Worldwide Interoperability for Microwave Access). In view of the further development regarding exposure to WLAN and WiMax sources, it might be of consideration to implement also precautionary limits, additionally to GSM and UMTS frequencies, for WLAN and WiMax to minimize RF-EMF exposure. However, this aspect needs further clarification.

In order to meet the requirements of current, but especially future, mobile telecommunication, the mobile phone base station network has to be expanded and new technology standards have to be implemented. Currently, the fourth generation of technology standard, namely LTE (Long-term Evolution), is gradually introduced in different cities worldwide. It allows data transfers over 100 Mbit/s. Additionally, telecommunication providers have introduced new subscription structures, allowing free calls and text messages as well as mobile internet, irrespective of the type of subscription. This opens barriers to an increased use of mobile telephony, expecting a shift from lower fixed line telephony to increased mobile cellular telephone usage, as could already been observed according to data provided by the International Telecommunication Union (ITU, http://www.itu.int/en/ITU-D/Statistics/Pages/stat/default.aspx, accessed on 10.11.2013).

Overall, all these advances in mobile telecommunication technologies will result in new exposure sources and will substantially alter RF-EMF exposure patterns in the population. Research conducted in the framework of this dissertation allows making statements about the current exposure landscape of the general public. However, we could observe that EMFs are highly dynamic exhibiting a high spatial and temporal variability. We could demonstrate that a monitoring of RF-EMFs with personal exposimeters is very feasible for characterizing exposure levels in everyday environments and investigating temporal variations. In contrast, exposimeters are not appropriate for measuring near-field sources, as conclusions on the dose cannot be drawn from measured values. Identification of areas with critical exposure levels is possible. In such areas, however, data should be confirmed with spectrum analyzer measurements, as these devices are very accurate, allow for maxima identification, and are able to distinguish even between different operators. Characterization of RF-EMF sources in indoor settings, others than train stations or airports, like homes, spectrum analyzer measurements would be of advantage. Characterization of large-scale RF-EMF exposure does not allow drawing conclusions on the exposure situation of the population but allows estimating exposure over large regions as well as on country-level. However, only fixed-site transmitters and building characteristics can be considered and consequently does not reflect real life exposure situation. Studies assessing temporal trends in different environments and across various cities should use a study design based on a common data collection protocol with repetitive measurements. In addition, different measurement paths should be defined for characterization of the exposure situation in an areas in order to capture as much of the spatial variability as possible.

The fast-changing technological developments are accompanied by new challenges. Thus, new measurement devices are needed to asses new frequencies; a systematic monitoring with newly developed exposimeters, as the new Expom developed by the ETH Zurich, allows quantifying additional frequencies, such as LTE (up- and downlink sources combined). At Ghent University, a shirt was developed with integrated antennas to measure different signals, including LTE.

Monitoring studies investigating RF-EMF exposure are imperative. This approach permits evaluation of previously taken actions and suggests new preventive measures. So far it has not yet been systematically assessed which sources contribute more to the personal exposure to RF-EMF, near-field or far-field sources. Large measurement studies comparing RF-EMF exposure among different countries should be object of further research. In this context, a common study design in all countries is highly recommended, as it enables a more reliable and detailed comparison. Such exposure assessment studies could be performed with personal exposimeters able to quantify also sources from newer technology standards (LTE) and should signally monitor temporal development of RF-EMFs. Besides exposure monitoring, biological mechanisms which are affected should be further studied. Most importantly, studies on effects of low-dose exposure to RF-EMF should be planned on a long-term basis and conducted using personal exposimeters which are also able to measure LTE. Furthermore, when investigating a potential association between mobile phone use and adverse health effects, adjacent to studies focussing on brain tumours, behavioural aspects should be considered, especially in children and adolescents, as their lifetime cumulative dose increases, due to their longer-term use of mobile devices. Such a study has been initiated in the framework of the HERMES project (Health Effects Related to Mobile Phone Use in Adolescents).

From a methodological point of view, there are still open questions about the spatial and temporal radiation patterns of mobile phones, especially focussing on newer smartphones working on four and five frequency bands, respectively. UMTS mobile phones have been recommended due to their adaptive power control, regulating their output power during call establishment. It has to be further investigated, however, if this reduced amount of radiation is not compensated by emissions in stand-by mode.

To date, no major public health risks have emerged and could be proven by EMF research, but, in the light of current uncertainties regarding potential adverse health effects, minimizing exposure might be reasonable and requested.

The way forward…

A global research effort is highly needed to clarify health risks and translating findings into public policies to protect human health.

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