# Effects of radiofrequency electromagnetic field exposure on sleep quality

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# Summary


### Introduction and background

The use of wireless communication devices, which emit radiofrequency electromagnetic fields (RF-EMF), has increased in the past decades. According to the World Health Organization (WHO) mobile phone use is ubiquitous with an estimated 4.6 billion subscriptions globally. The missing knowledge about a biological mechanism and the attribution of non-specific symptoms of ill health to RF-EMF have led to an increased public concern about possible adverse health effects from this radiation. Persons attributing their symptoms to electromagnetic fields are called electro hypersensitive (EHS) individuals. One of the most often reported symptoms due to RF-EMF exposure are sleep disturbances. In several randomised double-blind human laboratory studies, changes in the sleep electroencephalogram (EEG) after exposure to RF-EMF were observed. The impact of these small changes on sleep quality and therefore on general well-being is unclear. Previous epidemiological studies have used a cross-sectional design, which is not appropriate for establishing causal relationships between exposure and outcome. Studies with a cohort design are therefore needed. Additionally, exposure assessment was mostly inadequate or only parts of the real exposure situation were taken into account. Personal measurement devices (exposimeters) have become available a few years age. In large epidemiological studies, it is very time-consuming and costly to use such devices. Other exposure assessment methods are therefore needed.

### Aims

The main aim of this thesis was to investigate the association between personal RF-EMF exposure and sleep quality by using objective as well as subjective data. To predict personal exposure to RF-EMF a comprehensive exposure assessment method was applied. In a sub analysis, we characterized EHS individuals and we investigated the association between RF-EMF exposure and non-specific symptoms of ill-health in EHS individuals.

**Methods**

This thesis was part of the QUALIFEX project (a prospective cohort study on radiofrequency electromagnetic field exposure and health related quality of life) which is embedded in the National Research Program 57 (NRP-57) about non-ionising radiation.

The health effect of RF-EMF exposure was investigated in a cohort study which consisted of a baseline survey in May 2008 and a follow-up survey one year later. Questionnaires entitled „Environment and Health“ were sent out to 1375 randomly selected study participants in the region of Basel (Switzerland). Information on sleep quality, on exposure relevant factors, on EHS status and on various confounding factors was collected. By means of a pre-study, which was not part of this thesis, a comprehensive exposure assessment method was developed. To predict personal exposure to far-field RF-EMF (e.g mobile phone base stations or radio transmitters), a validated full exposure prediction model was used which was developed based personal exposure measurements of 166 study participants who took part in a pre-study. Exposure to close to body sources was assessed using self-reported data on mobile phone and cordless phone use. Objective data of mobile phone use from network operators for participants who gave informed consent were additionally collected. For a nested sleep study, 120 participants out of the baseline survey took part in a nested sleep study to verify our previous results. Sleep quality and sleep behavior was assessed using actigraphy and exposure to RF-EMF was measured by means of personal exposimeters.

**Results**

For the baseline survey, mean calculated RF-EMF exposure to all relevant sources of all 1375 study participants was 0.12 mW/m$^2$ (0.21 V/m). Exposure at the follow-up survey was 0.13 mW/m$^2$ (0.22 V/m) and therefore comparable with the baseline exposure. No consistent association between RF-EMF exposure and self-reported sleep quality neither in the baseline analysis (cross-sectional analysis) nor in the cohort analysis (longitudinal analysis) was observed. In the nested sleep study, objective data on exposure and sleep quality did not yield any association between exposure and sleep quality. General health problems were more common in EHS individuals compared to non-EHS individuals. Nevertheless, no association between health problems and exposure status could be observed in EHS individuals.

**Conclusions and outlook**

The QUALIFEX project was the first study which applied a cohort design to investigate the association between RF-EMF exposure and sleep quality. Additionally, we were able to verify our results of the cohort study with objective data obtained in a nested sleep study. Overall, we found no consistent association between self-reported as well as objectively measured sleep quality and exposure to relevant RF-EMF sources in everyday life. Our results increase the evidence for a true absence of an effect of RF-EMF exposure on sleep quality. Our study used a very comprehensive exposure assessment method which included far-field sources as well as close to body sources. In general, exposure levels were very small and changes between the baseline and the follow-up survey were marginal. Hence, with our study no conclusions can be drawn regarding potential health effects of higher exposure levels. In future studies, more data on long-term effects have to be collected. Additionally, the exposure situation in everyday life should be monitored because new technologies operating with RF-EMF are continuously arising.

# Zusammenfassung


**Einleitung und Hintergrund**

Der Gebrauch von Kommunikationsmitteln, die mit hochfrequenter elektromagnetischer Strahlung (HF-EMF) arbeiten, hat in den letzten Jahren stark zugenommen. Gemäss WHO (Weltgesundheitsorganisation) waren bis anfangs 2010 weltweit 4.6 Milliarden Mobiltelefonverträge abgeschlossen worden. Das fehlende Wissen über einen möglichen biologischen Wirkungsmechanismus und das Auftreten von unspezifischen Symptomen, die HF-EMF zugeschrieben werden, führen zu wachsender Besorgnis vor negativen Gesundheitsauswirkungen in der Bevölkerung. Personen, die ihre Symptome elektromagnetischen Feldern zuschreiben, werden als elektrosensibel bezeichnet. Als häufiges Symptom im Zusammenhang mit HF-EMF, insbesondere mit Mobilfunkantennen, wurde eine Beeinträchtigung der Schlafqualität genannt. In mehreren doppelblinden randomisierten Laborstudien wurde gezeigt, dass es nach der Exposition durch HF-EMF zu Veränderungen im Schlafelektroenzephalogramm (EEG) kommt. Welche Auswirkungen diese Veränderungen jedoch auf die Schlafqualität und damit auf das Wohlbefinden haben, ist unklar. Bisherige epidemiologische Studien benutzten ein Querschnittsdesign, welches nicht dazu geeignet ist, unmittelbar auf kausale Zusammenhänge zu schliessen. Es sind daher Studien mit einem Kohortendesign notwendig, bei dem Studienteilnehmer über längere Zeit hinweg beobachtet werden. Zudem war in den bisherigen Studien die Expositionsabschätzung meist unzureichend oder es wurden oft nur Teilaspekte der Exposition angeschaut. Seit ein paar Jahren gibt es persönliche Exposimeter, die es ermöglichen HF-EMF im normalen täglichen Leben zu messen. In grossen epidemiologischen Studien ist es aber sehr kosten- und zeitaufwändig, solche Geräte einzusetzen. Andere Expositionsabschätzungsmethoden, wie beispielsweise eine Modellierung der Exposition, sind nötig.

**Ziele**

Das Hauptziel dieser Dissertation war es, den Zusammenhang zwischen persönlicher Exposition durch HF-EMF und der Schlafqualität zu untersuchen und dabei sowohl subjektive wie auch objektive Daten zu berücksichtigen. Zur Abschätzung der Exposition durch HF-EMF wurde eine umfassende Expositionsabschätzungsmethode angewendet. In einer Subanalyse wurden zudem spezifisch elektrosensible Personen auf den Zusammenhang zwischen der Exposition durch HF-EMF und unspezifischen Symptomen untersucht.

**Methodik**

Diese Dissertation wurde im Rahmen des QUALIFEX Projekts (Exposition durch HF-EMF und gesundheitsbezogene Lebensqualität) durchgeführt, das Teil des Nationalen Forschungsprogramms 57 (NFP-57) über nicht-ionisierende Strahlung ist.

Der Effekt von HF-EMF auf die Schlafqualität wurde in einer Kohortenstudie untersucht, die aus einer Erstbefragung im Mai 2008 und einer Zweitbefragung ein Jahr später bestand. Die zufällig ausgewählte Stichprobe bei der Erstbefragung umfasste 1375 Studienteilnehmer aus der Region Basel, Schweiz. In einem Fragebogen zu „Umwelt und Gesundheit" wurden Informationen zur Schlafqualität, zu expositionsrelevanten Faktoren, zur Elektrosensibilität und zu möglichen Störvariabeln gesammelt. Mit Hilfe einer Vorstudie (Exposimeterstudie), die nicht Teil dieser Dissertation ist, wurde eine umfassende Expositionsabschätzungsmethode entwickelt und alle relevanten Fernfeldquellen (z.B. Mobilfunkbasisstationen und Radiosender) wurden dabei berücksichtigt. Die Exposition durch Nahfeldquellen (Mobil- und Schnurlostelefon) wurde mit selbstberichteten Angaben zu Mobil- und Schnurlostelefongebrauch und mit objektiven Daten von Netzbetreibern abgeschätzt. Aus der Erstbefragung wurden zur Überprüfung des Zusammenhangs zwischen Exposition und Schlafqualität 120 Personen ausgewählt, bei denen während zwei Wochen die Schlafqualität mittels Aktigraphie und die Exposition mit einem persönlichen Dosimeter gemessen wurden.

**Resultate**

Die mittlere berechnete HF-EMF Exposition der 1375 StudienteilnehmerInnen der Erstbefragung durch alle relevanten Quellen war 0.12 mW/m$^2$ (0.21 V/m). Die Exposition war bei der Zweibefragung ein Jahr später mit 0.13 mW/m$^2$ (0.22 V/m) nahezu gleich. Es konnte kein konsistenter Zusammenhang zwischen der HF-EMF Exposition und der selbstberichteten Schlafqualität gefunden werden, weder bei der Querschnittsanalyse der Erstbefragung noch bei der Kohortenanalyse (längerfristige Effekte). Auch die objektiv gemessenen Daten zu Exposition und Schlafqualität in der eingebetteten Schlafstudie brachten keinen Zusammenhang zwischen Exposition und Schlafqualität hervor. Generelle gesundheitliche Probleme kamen bei elektrosensiblen Personen häufiger vor als bei der übrigen Studienpopulation. Allerdings konnte auch bei jenen Personen kein Zusammenhang zwischen gesundheitlichen Problemen und HF-EMF Exposition festgestellt werden.

**Schlussfolgerung und Ausblick**

Im QUALIFEX Projekt wurde erstmals ein Kohortenstudiendesign angewendet um den Zusammenhang zwischen HF-EMF Exposition und der Schlafqualität zu untersuchen. Zudem konnten wir die Resultate der Kohortenstudie mit objektiven Daten zu Exposition und Schlafqualität in einer eingebetteten Schlafstudie überprüfen. Gesamthaft lässt sich sagen, dass wir keinen konsistenten Zusammenhang weder mit selbstberichteter noch mit gemessener Schlafqualität und alltäglicher HF-EMF Exposition von verschiedenen Quellen finden konnten. Unsere Studienresultate steigern die Evidenz für ein Fehlen von einem Effekt von alltäglicher HF-EMF Exposition auf die Schlafqualität. Zudem war unsere Studie die erste epidemiologische Studie, die eine umfangreiche Expositionsabschätzungsmethode anwendete, die die wichtigsten Expositionssituationen berücksichtigte (Nahfeld- und Fernfeldquellen). Allerdings muss gesagt werden, dass die Expositionsniveaus sehr niedrig waren und die Expositionsunterschiede zwischen den beiden Befragungen sehr gering waren. Mit den Resultaten der QUALIFEX Studie lassen sich demzufolge keine Rückschlüsse über Effekte von stärkeren Expositionen ziehen. In zukünftigen Studien müssen weitere Daten zu Langzeiteffekten gesammelt werden. Zudem muss die Expositionssituation weiterhin überwacht werden, da sich stetig neue Technologien, die auf hochfrequenter Strahlung basieren, entwickeln.

# List of abbreviations

| | |
|---|---|
| 95%-CI | 95%-confidence interval |
| DECT | Digital enhanced cordless telecommunication |
| EEG | Electroencephalography |
| EHS | Electromagnetic hypersensitivity |
| EMG | Electromyography |
| EOG | Electrooculography |
| ESS | Excessive daytime sleepiness |
| GSM | Global system for mobile communication signals |
| HIT-6 | Headache impact test with six items |
| Hz | Hertz |
| ICNIRP | International commission of non-ionizing radiation protection |
| IEI-EMF | Idiopathic environmental illness with attribution to electromagnetic fields |
| LTE | Long term evolution (4th generation of mobile phone communication) |
| NRP 57 | National research program 57 |
| ONIR | Ordinance relating to protection from non-ionizing radiation |
| OR | Odds ratio |
| PSG | Polysomnography |
| PSQI | Pittsburgh sleep quality index |
| REM | Rapid eye movement |
| RF-EMF | Radiofrequency electromagnetic fields |
| RFID | Radiofrequency identification |
| ROS | Regression on order statistics |
| SAR | Specific absorption rate |

| | |
|---|---|
| SHS | Swiss health survey |
| Tetrapol | Terrestrial trunked radio police |
| UMTS | Universal mobile telecommunication system |
| V/m | Volt per meter (unit for electrical field strength) |
| $W/m^2$ | Watt per square meter (unit for power flux density) |
| WHO | World health organization |
| W-LAN | Wireless local area network |

# 1 INTRODUCTION

## 1.1 Electromagnetic fields and health impact Open research issues

In the last few decades, the use of electromagnetic fields, namely radiofrequency electromagnetic fields (RF-EMF) for wireless communication, has increased continuously (Frei et al. 2009b; Neubauer et al. 2007). According to the World Health Organization (WHO) mobile phone use is ubiquitous with an estimated 4.6 billion subscriptions globally[1]. In some parts of the world, mobile phones are the most reliable or the only phones available. Also wireless communication devices other than mobile phones (e.g. iPads) are used increasingly. Thermal effects of RF-EMF above a certain intensity level are well-established. The fast increase of this technology, the limited knowledge about health impacts, and about biological mechanism of low-level (non-thermal) RF-EMF exposure has led to public concern since the 1980's. In a representative Swiss study sample, 5% of the participants attributed various non-specific symptoms of ill-health to electromagnetic fields (Schreier et al. 2006). This phenomenon is called electromagnetic hypersensitivity (EHS) or idiopathic environmental illness with attribution to electromagnetic fields (IEI-EMF). The prevalences of EHS in other countries were also investigated and varied from 1.5% in Sweden (Hillert et al. 2002) to 8-10% in Germany (Blettner et al. 2009; Infas 2010). One reason for the different prevalences of EHS might be the absence of standardized diagnostic criteria. In the Swiss study, the most often reported health complaints attributed to EMF exposure were sleep disturbances (42.7%), followed by headache (33.8%) (Schreier

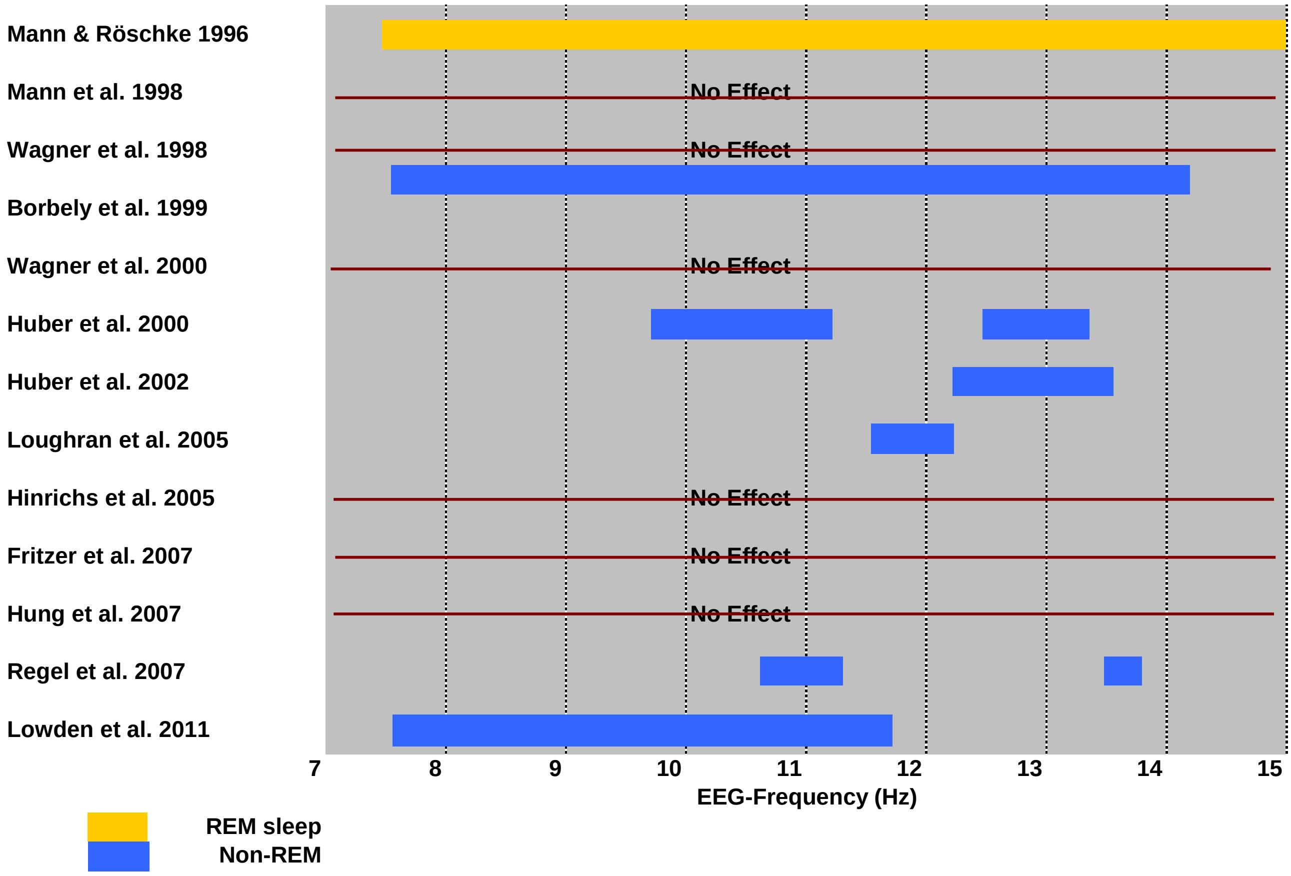
[1] http://www.who.int/mediacentre/factsheets/fs193/en/index.html

et al. 2006). These findings are in line with findings in other European countries, for example with the German survey conducted by the Institute for Applied Social Sciences between 2003 and 2010 (Infas 2010). Among the 10% of the participants who were classified as EHS individuals, the proportion of persons suffering from sleep disturbances was with around 11% stable over the years (2003-2010) and was the second most reported complaint due to RF-EMF exposure. Headache was the most often reported symptom in this survey.

In several laboratory studies under well-controlled conditions the association between RF-EMF exposure and the development of non-specific symptoms of ill-health was investigated. Exposure duration either through mobile phone handsets or through mobile phone base stations were normally between 30 and 60 minutes (Eltiti et al. 2007; Furubayashi et al. 2009; Hietanen et al. 2002; Johansson et al. 2008; Koivisto et al. 2001; Oftedal et al. 2007; Regel et al. 2006; Rubin et al. 2006; Wilen et al. 2006). Only in the study of Fritzer et al. (2007) exposure condition was applied during the whole night and in the study of Hillert et al., (2008) mobile phone like exposure was applied for three hours. Non-EHS as well as EHS individuals participated in these studies. Nearly all of these human laboratory studies did not find an association between the development of symptoms and RF-EMF exposure (Röösli 2008; Röösli et al. 2010b; Rubin et al. 2010).
Some of the studies observed the appearance of a nocebo effect. The nocebo effect describes the occurrence of non-specific symptoms of ill-health due to expectations (e.g due to concerns). Rubin et al., (2006) reported that participants developed symptoms during sham condition. In a study of Regel et al. (2006), a correlation between perceived exposure levels and symptoms was observed. But the true exposure level was not associated with the perceived exposure level. A nocebo effect was also observed in a study of Stovner et al. (2008), where participants experienced their typical mobile phone headache both with and without RF exposure.

As a consequence of the high prevalence of sleep disturbances attributed to RF-EMF and the lack of a biological mechanism for low level exposure, sleep quality and sleep mechanism have been key issues of EMF-research in the past few decades. Analyses during sleep were performed, because sleep is a state in which many intrinsic and extrinsic factors are eliminated and controlled. Laboratory studies have the advantage that biases can be reduced by randomisation and well-controlled exposure conditions. Cross-over designs are most suitable for this type of research. In a cross-over study, each participant randomly passes through all exposure situations, real exposure as well as sham-exposure. The advantage of this study design is that effects of confounding covariates can be nearly eliminated, because each crossover study participant serves as his or her own control. Additionally, this design has a rather high statistical power.

Since the mid 90's, various human laboratory studies on RF-EMF exposure and sleep were conducted. In *Figure 1.1* an overview of relevant findings in human laboratory studies of RF-EMF exposure on the sleep EEG is presented. Sleep quality and brain activity during sleep was measured with polysomnographic devices (for background information see 2.2.2). In the mid 90's, Mann and Röschke (1996) found that sleep latency (the latency before sleep onset following bed time) was reduced in subjects exposed to a GSM (Global System for Mobile Communication) signal during sleep and REM phase (Rapid Eye Movement) was shorter than in the control condition. These findings could not be confirmed in further studies of this research group (Mann et al. 1998) as well as not from other research groups. Borbély et al. (1999) found an enhanced activity in the spindle frequency range (8 – 14 Hz) of the EEG during sleep stage II (for background information see 2.2.1) of the non-REM phase after exposure to a signal being turned on and off every 15 minutes. These findings could be replicated quite consistently in several other studies (Huber et al. 2000; Huber et al. 2002; Regel et al. 2007) which were not only conducted from this research group (Loughran et al. 2005). Possible implications of these alterations in sleep stage II on sleep quality or more generally on quality of life are so far not clear. Short-term effects of RF-EMF on subjective sleep quality were considered in some of the presented studies (Borbely et al. 1999; Lowden et al. 2011) and no change in subjective sleep quality after exposure was observed.




*Source: Adapted from Loughran, NRP57 workshop, Zurich, Oct. 2008*

***Figure 1.1:*** *Sleep EEG results from human experimental studies*

Human laboratory studies are less appropriate for examining possible health effects, long-term effects, or effects of everyday life RF-EMF exposure. Therefore, several epidemiological cross-sectional studies (Berg-Beckhoff et al. 2009; Hutter et al. 2006; Thomas et al. 2008) and field-intervention studies (Danker-Hopfe et al. 2010; Leitgeb et al. 2008) have been conducted to investigate the association between RF-EMF exposure in everyday life and subjective sleep quality. In these studies, no effect of RF-EMF exposure on subjective sleep quality was observed.

One limitation of these epidemiological and field-intervention studies was the use of a cross-sectional study design. In cross-sectional studies, exposure and outcome are determined at the same time point. Therefore, the temporality of exposure and outcome usually is unknown and one cannot directly conclude on a causal relationship between outcome and exposure. Also, long-term effects are not represented in results of cross-sectional studies. Effects of prolonged RF-

EMF exposure in the usual sleep conditions on subjective sleep quality have so far not been investigated.

Another problem of previous epidemiological studies on RF-EMF and health impact is the assessment of RF-EMF exposure. Early studies which investigated the effects of radiofrequency electromagnetic fields (RF-EMF) and non-specific symptoms of ill-health (Navarro et al. 2003; Santini et al. 2002) found adverse effects. A major problem of these early studies was the deficient exposure assessment by using self-reported distance to the next mobile phone base station. Especially in combination with self-reported symptoms, this exposure proxy is likely to introduce bias. This means that people who attribute their symptoms to exposure from mobile phone base stations are more likely to underestimate the distance from their place of residence to the closest mobile phone base station. In more recent studies, spot measurements in sleeping rooms (Berg-Beckhoff et al. 2009; Hutter et al. 2006; Thomas et al. 2008) were used. These spot measurements in the sleeping room represent more accurately exposure of everyday life (Frei et al. 2010). However, close to body sources like mobile phone or cordless phone use as well as exposure at work or during everyday life activities are not considered. In addition, temporal variations cannot be taken into account. In the past few years, personal exposure meters (exposimeters) became available and temporal and spatial variability can be measured. The use of exposimeters is widely recommended in order to characterize the exposure distribution in a certain population (Neubauer et al., 2007; Ahlbom et al., 2008). Several countries and research teams have conducted measurement studies to assess personal RF-EMF exposure to multiple sources in the everyday environment (Joseph et al. 2010; Viel et al. 2009). Exposure levels were in all studies far below the ICNIRP reference levels. In all countries except for the Netherlands, the highest total exposure was measured in transport vehicles (trains, car, and busses), mainly due to radiation from mobile phone handsets (up to 97%). Exposure levels were in general lower in private houses or flats than in offices and outdoors. At home, contributions from various sources were quite different between countries (Joseph et al. 2010). But a comparison of these studies is difficult because of different measurement devices and because of different analysis procedures that have been used. Although exposimeters are recommended for epidemiological studies, the organizational effort for planning and conducting a study with a large sample size using exposimeters is time-consuming for participants and very expensive for the research team. Another problem is that participants might influence their measurements by putting the device at places where high exposure levels are expected. In combination with self-reported symptoms, this might introduce unreliable results and bias.

The missing biological mechanism of low level RF-EMF exposure leads to the problem that we do not know if a specific frequency of RF-EMF is important for health impact, if there is a threshold above which health disturbances occur or maybe if it is a dose response issue. Therefore it is crucial to use a comprehensive exposure assessment method which includes several exposure surrogates and takes the different lifestyle of every individual into account.

This thesis focuses on the investigation of subjective sleep quality and longer-term RF-EMF exposure. Therefore, we conducted the first cohort study which investigates the association between RF-EMF exposure and sleep. Due to the unknown biological mechanism, we used a very comprehensive exposure assessment method which includes several exposure surrogates and takes far-field as well as close to body sources into account. In a further step, the phenomenon of EHS will be investigated with the cohort data.

## 1.2 Objectives of QUALIFEX and structure of the thesis

This thesis was conducted in the framework of the QUALIFEX project (radiofrequency electromagnetic field exposure and health related quality of life: a prospective cohort study). This project is embedded in the National Research Program 57 (NRP 57) about non-ionizing radiation – health and environment and is the only epidemiological study in this program.

The QUALIFEX project consisted of three parts:

- Determination of the RF-EMF exposure situation in a Swiss population sample (exposimeter study)
- Development and evaluation of an exposure assessment method
- Investigation of the association between health related quality of life and RF-EMF exposure (health study)

The whole QUALIFEX project was conducted in Basel and its surroundings. The schematic illustration of the QUALIFEX project is shown in *Figure 1.2.*

The determination of the RF-EMF exposure situation and the development of an exposure assessment method are covered by the thesis of Frei (2010). These parts are grey colored in *Figure 1.2*.

The overall goal of the present thesis was to evaluate and apply appropriate exposure assessment methods and to investigate the association between RF-EMF exposure and sleep quality. The evaluation of the exposure assessment methods was based on data of the exposimeter study and the investigation of the association between RF-EMF exposure and sleep quality was based on data of the health study. The health study was divided in a baseline survey and in a follow-up survey. Additionally, we recruited participants from the baseline survey to take part in a nested sleep study.

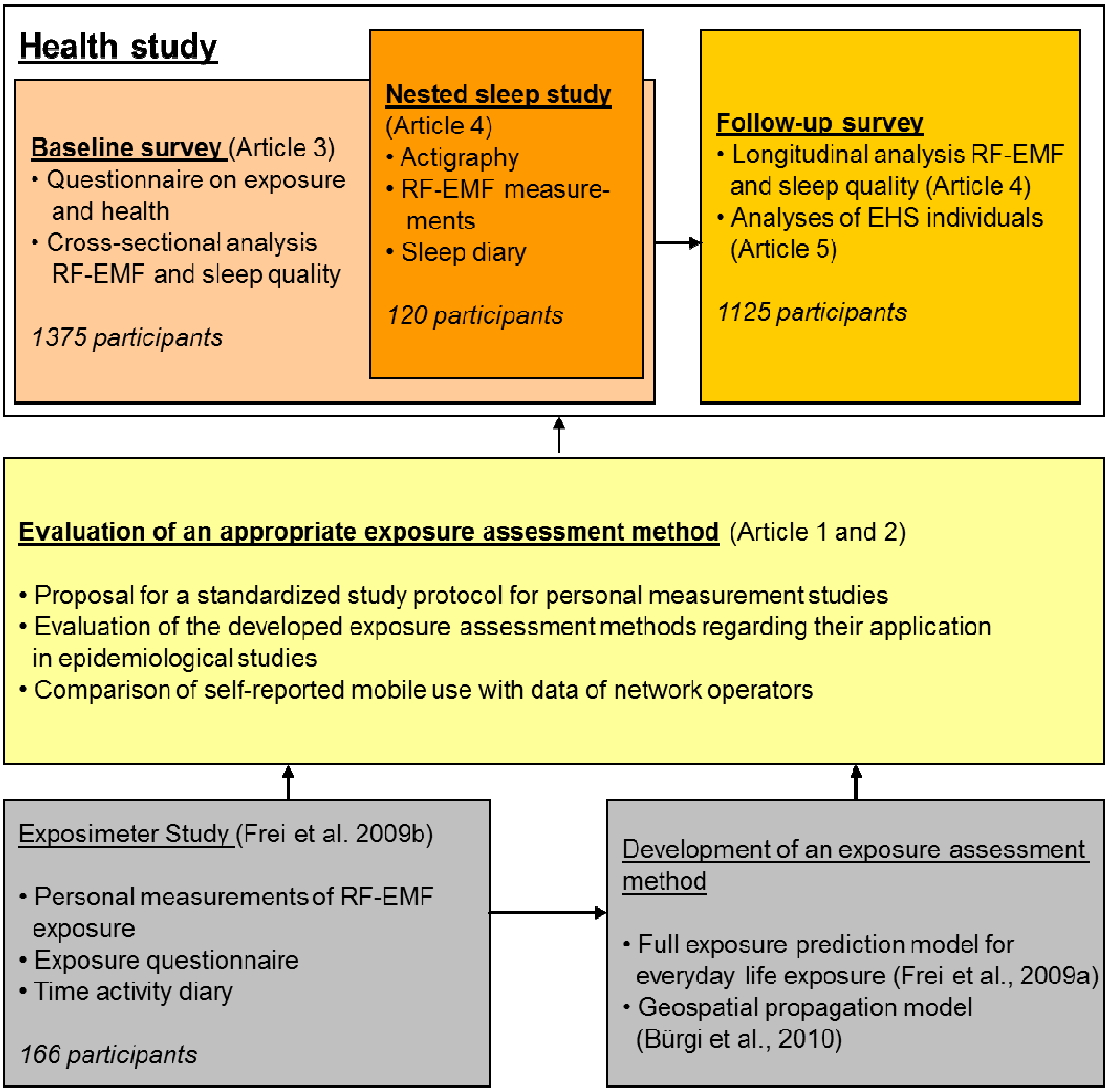



***Figure 1.2:*** *Overview of the QUALIFE project. The exposimeter study and the development of an exposure assessment method was part of the thesis of Patrizia Frei (2010)*

### 1.2.1 Aims of the thesis and general methods

In the following, the three aims A) to C) of this thesis and the respective methods are presented.

**A) *To evaluate and apply appropriate exposure assessment methods***

⇒ ***Evaluation of a standardized study protocol to measure personal RF-EMF exposure***

In the exposimeter study, we gained lot of experience about the handling of personal measurement devices and about study procedure and data analysis. Contemporaneously to our exposimeter study, different countries conducted personal measurement studies as well. Different study procedures and analysis were used. In Article 1 of this thesis, together with other researchers who are experienced with personal dosimetric measurement studies, we proposed a standardized study protocol to be able to compare future studies with personal measurement devices in different countries.

⇒ ***Exposure assessment in the QUALIFEX project***

In the QUALIFEX project, different exposure assessment methods (Bürgi et al. 2010; Frei et al. 2009a) were previously developed. They were based on one-week measurements of 166 participants, where spatial and temporal variability of RF-EMF exposure in everyday life was assessed (Frei et al. 2009b). To evaluate the different exposure assessment methods regarding their application in epidemiological studies, we compared in this thesis predicted exposure at home from a geospatial propagation model (sources from fixed site transmitters) (Bürgi et al. 2010) with the corresponding measured mean exposure from fixed site transmitters in article 2. Data for these analyses were collected in the exposimeter study. Additionally, information on self-reported mobile phone use was validated with objective data of network operators. These data were collected in the health study.

An overview of the evaluation of exposure assessment methods used in the QUALIFEX project is given in Article 2.

## B) *To investigate the association between RF-EMF exposure and self-reported sleep quality and sleep behaviour*

Aim B) was investigated in the different parts of the health study.

⇒ ***Cross-sectional analyses (baseline survey)***

In May 2008, we sent questionnaires to 4000 randomly selected inhabitants of Basel and its surroundings who were between 30 and 60 years old. To assess self-reported sleep quality, we used seven questions from the Epworth Sleepiness Scale (ESS) to investigate daytime sleepiness and four standardized questions from the Swiss Health Survey to examine self-reported sleep disturbances (Schmitt et al. 2000).

Six different exposure surrogates were used to predict RF-EMF exposure:

- Exposure in everyday life: We used a validated full exposure prediction model based on 166 individual weekly measurements collected in the exposimeter study and on exposure relevant factors (Frei et al. 2009b).
- Exposure at home: Exposure at home was predicted by using a geospatial propagation model which predicts exposure at home from fixed site transmitters (Bürgi et al. 2010).
- Exposure during night: Night exposure was calculated based on the above mentioned geospatial propagation model and relevant exposure factors during night were included.
- Exposure to mobile phones: The use of mobile phones was assessed by using self-reported data from the questionnaires. Additionally, mobile phone use was assessed with operator data for participants who gave informed consent.
- Exposure to cordless phones: Self-reported data from the questionnaires were used to assess exposure to cordless phones.
- Self-estimated exposure: In the questionnaire, participants had to estimate their exposure status compared to the Swiss population and to indicate whether they felt they were equally, less or more exposed in comparison to the average of the Swiss population.

By means of logistic regression models adjusted for relevant confounders, the association between RF-EMF exposure and self-reported sleep quality was investigated.
The results are given in Article 3.

⇒ ***Longitudinal analysis (baseline and follow-up survey)***

One year after the baseline survey, in May 2009, (see cross-sectional study and Article 3), the same questionnaire was sent out to the 1375 responders of the baseline survey. Daytime sleepiness, self-reported sleep quality, potential confounders and RF-EMF exposure were assessed in the same way.
To investigate possible long-term associations between various RF-EMF exposure surrogates and self-reported sleep quality, we performed two different analyses using multivariable regression models adjusted for relevant confounders: a cohort analysis and a change analysis.

- Cohort analysis: We evaluated the association between exposure at baseline and change in sleep quality between baseline and follow-up survey.
- Change analysis: We investigated the influence of change in the exposure situation between the baseline and the follow-up survey on changes in self-reported sleep quality between these two surveys.

The results of this longitudinal analysis are presented in Article 4.

⇒ ***Nested sleep study***

In a nested sleep study, 120 of the 1375 participants of the baseline survey were recruited by telephone. Recruitment of the study participants took place between August 2008 and November 2009. In this subgroup, sleep behaviour was objectively measured during two weeks by means of an actigraphic device (AW7, Neurotecchnology, Cambridge, United Kingdom). Actigraphs contain omnidirectional accelerometers that digitally count wrist movements. Participants were asked to press an event marker on the actigraph each night when they had the intention to sleep. Additionally, participants filled in a sleep diary where they reported their bed time, wake time and self-estimated sleep quality. The sleep diary was a backup when participants forgot to press the event marker. To calculate the different sleep parameters, we used the software of the manufacturer (Actiwatch

Activity and Sleep Analysis 7, Version 7.23, Cambridge Neurotechnology). For automatic determination of sleep start, the algorithm looks for a period of at least ten minutes of consecutively recorded immobile data following bed time, with no more than one epoch (15s) of movement within that time. The start of this defined period is classified as sleep start. For sleep end, the algorithm looks backwards from the last sample in the analysis window for a specific consecutive period of activity below the threshold and classifies the last epoch in this period as sleep end.

For the analysis two sleep parameters were derived from actigraphic measurements:

- Total sleep duration: difference between sleep end and sleep start, excluding waking phases
- Sleep efficiency: percentage of time in bed that a person actually sleeps

To obtain information about habitual and self-reported sleep behaviour, participants had to fill in the Pittsburgh Sleep Quality Index (PSQI) (Buysse et al. 2006) at the beginning of the two weeks measurement period.

RF-EMF exposure in the bedrooms was measured for one week using the EME SPY 120 measurement device (exposimeter), which measures exposure to 12 frequency bands ranging from radio FM (frequency modulation; 88-108 MHz) to W-LAN (Wireless local area network; 2.4-2.5 MHz) (for more details see also Table 2.2). Three different exposure parameters were used:

- Measurements from all measured sources during night in the sleeping room
- Measurements in the sleeping room only from fixed site transmitters
- Measurements during the day (participants carried around the exposimeter during one typical day of the two week measurement period).

Mean exposure values were calculated using the robust regression on order statistics (ROS) method (Röösli et al. 2008).

Because of repeated measures data within subjects, we calculated a random intercept model with autocorrelation of one day lag. All models were adjusted for

sex, age, physical activity, smoking status, season, weekday, bedtime, percent fulltime equivalent, educational level, body mass index, alcohol consumption and presence of a bed partner. Shift workers were not recruited for this study.
The results of this nested sleep study are given in Article 4.

## C) *To evaluate associations between RF-EMF exposure and electromagnetic hypersensitivity*

To evaluate the association between RF-EMF exposure and EHS, questionnaire data of the health survey (baseline and follow-up survey) were analysed.
We compared the self-declared EHS status at baseline and at follow-up. Moreover, socio-demographic factors, exposure situation and health status of EHS individuals were compared with the rest of the study population. Additionally, we investigated the association between RF-EMF exposure and non-specific symptoms of ill health in EHS individuals.
In the absence of an internationally established criteria for the diagnosis of EHS, we assessed EHS status with the following questions: “Are you electro hypersensitive?” and “Do you think that you develop detrimental health symptoms due to electromagnetic pollution in everyday life?”. Participants answering “Yes” to the first question were called EHS individuals. Those who answered “Yes” to the second question were defined as “attributers”. Prevalence of EHS was calculated using adjustments for age and gender. Non-specific symptoms of ill health were assessed using validated and standardized questions:

- Headache (Headache Impact Test, HIT-6)
- Daytime sleepiness (ESS)
- Sleep disturbances (questions from the SHS)
- Tinnitus

Comparisons of socio-demographic factors, health status and exposure situation between the three different groups (non-sensitive, attributers and EHS individuals) were done with chi-square tests in the case of binomial variables and Kruskal-Wallis tests in the case of cored or ranked data. In EHS individuals, the influence of several RF-EMF exposure surrogates on various somatic complaints was investigated by means of multiple linear regression models.

Results of these analyses are presented in Article 5.

# 2 BACKGROUND

## 2.1 Electromagnetic spectrum

The electromagnetic spectrum ranges from extremely low frequencies (frequency range: <1000 kHz), which are associated for example with household electric current, to radio waves (1000 kHz to 10 GHz), microwaves (10 GHz to 1 THz), infrared radiation (1 THz to 100 THz), visible light (100 THz), ultraviolet radiation (1000 THz) and very high frequencies like short wavelengths of X-rays and gamma rays (> 1000 THz). The electromagnetic spectrum can be divided in a ionizing and a non-ionizing part. Ionizing radiation (frequency $>10^{15}$ Hz) is well known to ionize atoms and molecules and to disrupt molecular bonds. In contrary, non-ionizing radiation does not have sufficient energy to disconnect electrons from the atomic shell. Above a certain intensity level low frequency electromagnetic fields (frequency range: <100 kHz) are able to induce electrical fields and currents inside the body. The induced currents may interfere with the functions of the nervous system and stimulate nerve tissues. Radiofrequency electromagnetic fields (frequency range: 100 kHz to 300 GHz) can heat biological tissues (ICNIRP 1998) and cause local damage to tissues or heat stress. The possible biological mechanism of low-dose non-ionizing radiation is unknown.

In this thesis, fields in the radiofrequency range are of interest. RF-EMFs are mostly used for wireless communication technologies like mobile phone and cordless phone use, wireless internet or radio and broadcast transmitters.

### 2.1.1 RF-EMF reference levels

The International Commission on Non-Ionizing Radiation Protection (ICNIRP) releases guidelines for limiting exposure to EMF against known adverse health effects. These reference levels deal with acute effects and restrict RF-EMF exposure to prevent heating effects. Long-term effects and possible low dose effects are not considered, because ICNIRP concluded that available data are insufficient to provide a basis for setting exposure restrictions for long-term effects (ICNIRP 1998). The restriction limits for RF-EMF recommended by ICNIRP are based on the specific absorption rate (SAR). SAR gives information about the degree of energy which is absorbed by the tissue and is a tracer for the heating of the tissue. The SAR value is stated in watts per kilogram [$Wm^{-1}$] and depends on several factors, among them the exposure source and the field strength.

ICNIRP reference levels for radio and broadcast transmitters as well as for mobile phone base stations are given in *Table 2.1*. These reference levels are applied in several countries around the world. In Switzerland, in addition to these limits more restrictive precautionary exposure limits are applied. In February 2000, the Ordinance relating to Protection from Non-Ionizing Radiation (ONIR)[2] entered into effect. The aim of this ordinance was to protect the population against effects of non-ionizing radiation with exposure limit values. On the basis of a precautionary principle, ONIR regulates long-term exposure in places of sensitive use such as schools, apartments, offices and hospitals, with so called installation limit values (*Table 2.1*). These installation limit values are ten times lower than the ICNIRP reference levels and are based on technical, operational and economical criteria. Long-term exposure at places of sensitive use shall be kept as low as possible. The ONIR regulates exposure from fixed site transmitters. Mobile devices are excluded from this ordinance and are not explicitly legally regulated.

[2] Verordnung vom 23. Dezember 1999 über den Schutz vor nichtionisierender Strahlung (NISV), SR 814.710.

***Table 2.1:*** *Exposure limit values (ICNIRP guidelines, 1998) and installation limits for mobile phone base stations and radio/TV transmitters.*

| Source (frequency range) | Installation limit value | Exposure limit value |
|---|---|---|
| Radio/TV transmitter (88-830 MHz) | 3 V/m | 28 V/m |
| GSM (900 MHz) | 4 V/m | 41 V/m |
| GSM (1800 MHz) | 6 V/m | 58 V/m |
| UMTS (2100 MHz) | 6 V/m | 61 V/m |

### *2.1.2 Measuring personal RF-EMF exposure*

In the last years, personal dosimetric devices became available and are widely recommended for measuring personal RF-EMF exposure in epidemiological studies (Ahlbom et al. 2008; Neubauer et al. 2007). A big advantage of these devices is that they can be carried around and exposure can be measured not only at residential places but also in everyday life such as at work, during shopping or in public transport. Exposure to far-field sources like mobile phone base stations is accurately measured with personal dosimetric devices (Frei et al. 2009b). In contrary, exposure levels from mobile phones or cordless phones (close to body sources) are not adequately measured because the magnitude of exposure depends highly on the distance of the operating device and to the measurement device (Frei 2010).


***Figure 2.1:*** *EME Spy 120 exposimeter*

At the moment, two devices are on the market – the EME Spy 120/121 (Satimo, France) and the ESM-140 (Maschek, Germany). In the QUALIFEX study, we decided to conduct our personal measurements with the EME Spy 120 device. This measurement device has a detection limit of 0.05 V/m (0.0067 mW/m$^2$) and the maximal measurable value is 5 V/m. The EME Spy device (*Figure 2.1*) is able to differentiate between 12 different frequency bands (*Table 2.2*), has an optimal isotropy, and is able to store about 7000 measurements.

***Table 2.2:*** *Overview of measured RF-EMF sources by the EME Spy 120 (SATIMO, France) used in the QUALIFEX study.*

| **Source** | | **Frequency range (MHz)** | **Application** | **Type of exposure** |
|---|---|---|---|---|
| **FM** | | 88-108 | Radio transmitter | Far-field exposure |
| **TV** | TV3 | 174-223 | Broadcast transmitter | Far-field exposure |
| | TV4&5 | 470-830 | | |
| **Tetrapol** | | 380-400 | Authority radio | Far-field exposure |
| **Downlink** | GSM 900 | 880-915 | Mobile phone base station | Far-field exposure |
| | GSM 1800 | 1710-1785 | | |
| | UMTS | 1920-1980 | | |
| **Uplink** | GSM 900 | 925-960 | Mobile phone handsets | Close to body and |
| | GSM 1800 | 1805-1880 | | far-field exposure |
| | UMTS | 2110-2170 | | |
| **DECT** | | 1880-1900 | Cordless phones | Close to body and far-field exposure |
| **W-LAN** | | 2400 – 2500 | Wireless LAN | Close to body and far-field exposure |

## 2.2 Sleep

Sleep is a crucial part of our life. We spend approximately one third of our lives asleep. Sleep is defined as a period of inactivity and our body functions are reduced to the minimum during this time. This stage is very fast reversible – in contrast to a comatose stage.
Our life is driven by an inner clock, called circadian rhythm, which regulates waking and sleeping phases. This circadian cycle has a length of a little bit more than 24 hours and is controlled by endogenous factors like hormones (e.g. Melatonin). Under normal circumstances, the circadian rhythm is synchronized with the 24-hours-rhythm by external factors like social factors or light/dark cycle (Kryger et al. 2005).

### *2.2.1 Sleep architecture*

During the night, we pass through different sleep stages in a specific sequence (sleep architecture). We can roughly distinguish between two main sleep stages:

- REM-sleep (**R**apid **E**ye **M**ovement)
- Non-REM sleep

The REM sleep stage is regulated by the brain regions of the pons and the adjacent midbrain (Siegel 2001) During the REM sleep, the corresponding sleep-active neurons are fully activated and cause a complete loss of muscle tone in the postural muscles. REM-sleep is characterized as a “light” sleep and dreaming occurs typically during this stage. In addition, rapid eye movements under closed eyelids are typical for this stage of sleep.
For the regulation of non-REM sleep, sleep-active neurons of the forebrain region were identified (Siegel 2001). Activation of these neurons induces the non-REM sleep stage. Heating of the sleep-active neurons or the respective brain areas leads to an increase of their activity and therefore to an increase of non-REM sleep (Siegel 2001). Non-REM sleep can be divided into 4 sub stages. In sub stage 1 and 2, waking up and a light sleep is possible. In sub stage 3 and 4, sleep is very deep and it is difficult to wake up.

During one night, we pass through the different stages many times (*Figure 2.2*).

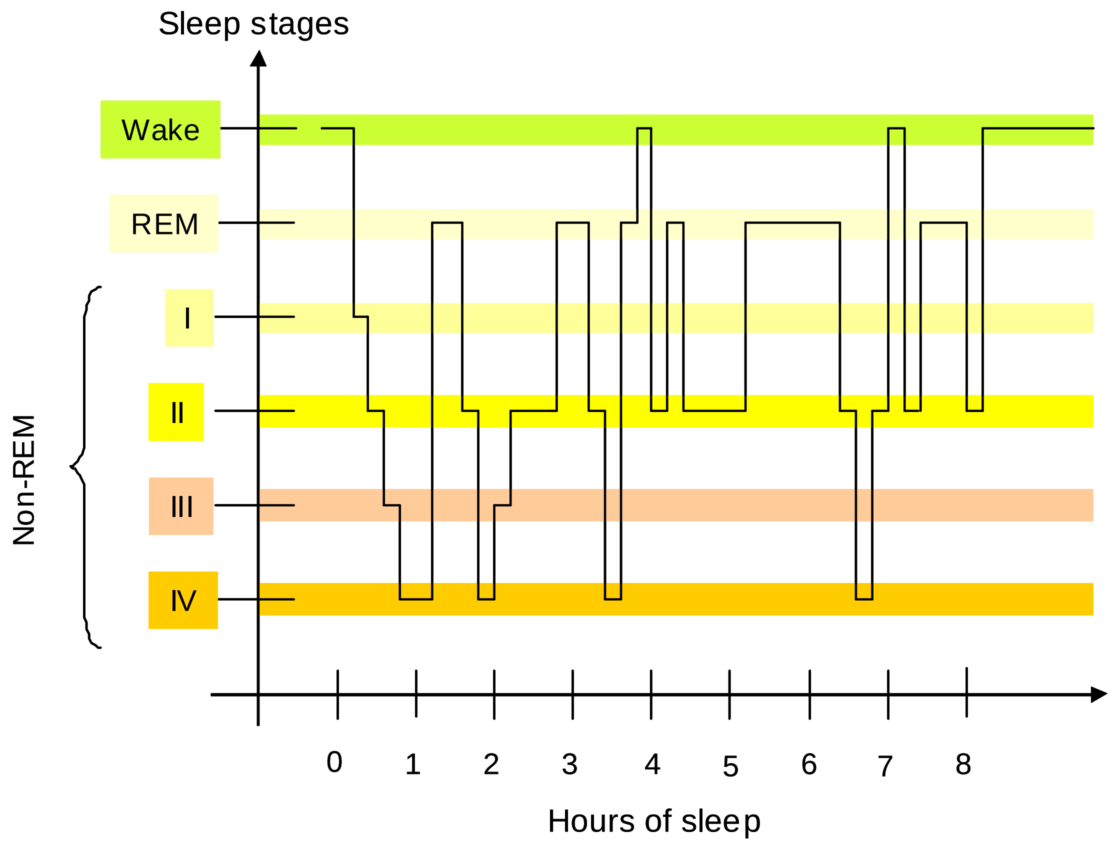
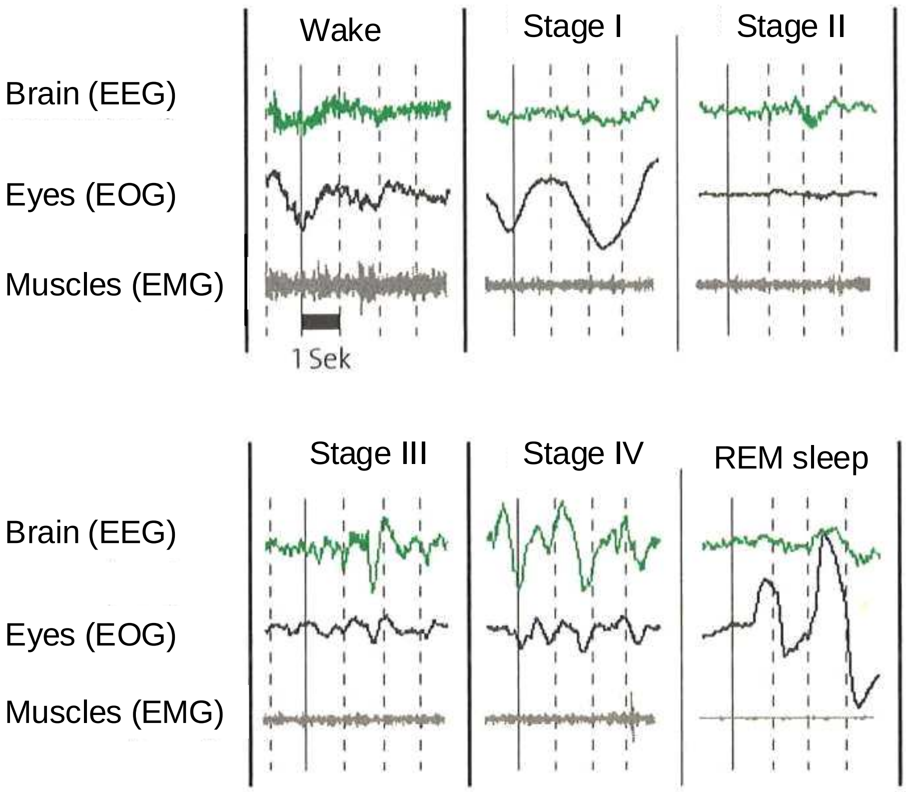



***Figure 2.2:*** *Typical sleep pattern during one night with eight hours of sleep.*

With increasing sleep duration, non-REM phases, especially sleep phase IV, become shorter and REM phases therefore get longer. With increasing age, people rarely reach sleep phase IV. The different sleep stages can be determined by frequency and amplitude of the brain activity which can be recorded by measurements (see 2.2.2). Typical EEG activity of waking and sleeping phases are presented in *Figure 2.3*.




*Source: Alexander Borbély, Schlaf, 2004, p. 11*

***Figure 2.3:*** *Typical EEG-activity in waking phases, in Non-REM sleep stages (stage I to IV) and in REM sleep stage.*

The REM phases are characterized by continuous EEG signals with small amplitudes and a frequency of about 8-13 Hertz [$s^{-1}$]. Sleep stage II of the Non-REM phase is characterized by irregular high amplitudes (K-Complex) and the appearance of sleep spindles (12-14 Hz). Until now, the physiological function of these sleep spindles are unknown. Sleep stage III and IV of the Non-REM phase have a lower frequency (0.75-4.5 Hz) and high amplitudes.

### *2.2.2 Measuring sleep quality*

In laboratory and clinical settings, sleep characteristics are recorded by means of polysomnography (PSG), where waking and sleeping phases are determined by brain activity (electroencephalography, EEG), eye movement (electrooculography, EOG) and muscle activity (electromyography, EMG). PSG measures volt-age/pressure differences on the body surface by means of electrodes which are positioned on the head to determine brain activity, near the eyes to estimate eye movement and under the chin to assess muscle activity. Results of these measurements are displayed on a screen and recorded on a computer. Due to the different signal shapes and frequencies, sleep stages can be distinguished. This method is designated to be the "gold standard", but has the disadvantage of only be applicable in standardized laboratory settings with a limited number of people.


***Figure 2.4:*** *Actiwatch (Neurotechonology, Cambridge, UK)*

As a low cost and easier method, actigraphy has been developed to measure different sleep parameters of the sleep macro architecture (e.g. sleep duration and sleep latency). Actigraphic devices are mainly carried at the wrist of the non-dominant hand (*Figure 2.4*). By means of accelerometer, the activity of the study participants during the night is measured and mobile (wake) versus immobile (sleep) phases can be distinguished. No conclusions about the different sleep stages can be drawn. Actigraphic devices are a reasonable alternative to polysomnography for larger studies which are conducted in the field and not in laboratory settings. Since the study participants can stay in their habitual surroundings, their sleep behaviour is not influenced by new and different sleep locations and conditions. Additionally, actigraphy can be used during several weeks for one individual.

### *2.2.3 Sleep disorders*

The average sleep duration in Switzerland is 7.25 hours per night during weekdays (Schmitt et al. 2000). According to a US study, sleep duration dropped about two hours per night over the last century and more than one hour per night over the past 40 years (Knutson 2010). With increasing age, sleep duration gets shorter and the amount of non-REM phases, especially during stage IV, decreases dramatically.

Sleep is influenced by several intrinsic and extrinsic factors and can be disturbed due to various factors. Usually, two main types of sleep disturbances are distinguished:

- ***Insomnia***: problems with falling asleep, maintaining the sleep during night, or waking up early in the morning without being able to fall asleep again. In this case, sleep is characterized by waking up often during night and sleeping superficially. Sleep stage IV of the non-REM phase is hardly ever achieved. Stress, noise or nutrition are only a few factors which can lead to insomnia.
- ***Hypersomnia***: is characterized by an excessive daytime sleepiness. This kind of sleep disorder leads to an impaired well-being and a decreased performance during the day. Reasons for hypersomnia may be an acute or chronic lack of sleep which is often caused by sleep apnoea. People suffering from sleep apnoea suffer from repeated breathing stops during night and these short breathing stops cause short wakening phases. According to the Swiss Sleep Society[3], prevalence of hypersomnia in the population is about 5%.

Sleep disturbances can have various reasons including psychological reasons, extrinsic reasons like noise exposure (Fyhri and Aasvang 2010) or somatic reasons like diabetes or overweight (Knutson and Van Cauter 2008). Even ethnicity does have an influence on sleep. Based on a literature review, Durrence and Lichstein (2006) concluded that African American people sleep worse than Caucasian Americans. African Americans need more time to fall asleep, they have a poorer sleep quality, a less deep sleep and they take more and longer naps. Also prevalence of sleep-disordered breathing was higher in African Americans.

[3] http://www.swiss-sleep.ch/dokumente/grundlage_disorders_d.pdf

# 3 EXPSOURE ASSESSMENT

# **Article 1:** Conduct of a personal radiofrequency electromagnetic field measurement study: proposed study protocol

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ENVIRONMENTAL HEALTH

METHODOLOGY Open Access

# Conduct of a personal radiofrequency electromagnetic field measurement study: proposed study protocol

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## Abstract

**Background:** The development of new wireless communication technologies that emit radio frequency electromagnetic fields (RF-EMF) is ongoing, but little is known about the RF-EMF exposure distribution in the general population. Previous attempts to measure personal exposure to RF-EMF have used different measurement protocols and analysis methods making comparisons between exposure situations across different study populations very difficult. As a result, observed differences in exposure levels between study populations may not reflect real exposure differences but may be in part, or wholly due to methodological differences.

**Methods:** The aim of this paper is to develop a study protocol for future personal RF-EMF exposure studies based on experience drawn from previous research. Using the current knowledge base, we propose procedures for the measurement of personal exposure to RF-EMF, data collection, data management and analysis, and methods for the selection and instruction of study participants.

**Results:** We have identified two basic types of personal RF-EMF measurement studies: population surveys and microenvironmental measurements. In the case of a population survey, the unit of observation is the individual and a randomly selected representative sample of the population is needed to obtain reliable results. For microenvironmental measurements, study participants are selected in order to represent typical behaviours in different microenvironments. These two study types require different methods and procedures.

**Conclusion:** Applying our proposed common core procedures in future personal measurement studies will allow direct comparisons of personal RF-EMF exposures in different populations and study areas.

## Background

There has been a substantial increase in environmental exposure to radio frequency electromagnetic fields (RF-EMF) over the last few decades due to the introduction of new technologies, especially those related to wireless communication [1]. This development has led to concerns regarding possible effects of exposure to environmental RF-EMF on health [2-4].

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Until now RF-EMF risk assessment has been hampered by the lack of reliable exposure assessment methods. Day-to-day exposure to RF-EMF comes from many different sources producing large variability in small-scale spatial and temporal exposure patterns. Prior to the availability of personal measurement devices, measurement of RF-EMF was complex and time consuming. In particular, concurrent measurements of different RF-EMF sources in many locations, long term measurements and measurements when moving were very challenging. As a result, previous measurement studies have focussed mainly on maximum exposure levels occurring over space and/or time, as appropriate for assessing compliance with safety limits, but not on exposure patterns in the general population such as average personal exposure, time spent above a threshold or rate of change. These quantities are of more interest for health risk assessments and for epidemiological studies. Thus, information about the total RF-EMF exposure of individuals in different populations is scarce. Only crude methods have been used for exposure assessment in epidemiological studies such as self-reported use of mobile phones [5,6], spot measurements of specific sources [7,8], or distances between residential addresses and the nearest transmitter. Distance was shown to be a modest RF-EMF exposure proxy with respect to broadcast transmitters but was inaccurate for mobile phone base stations [1,9-13].

Personal exposure to RF-EMF depends on exposure levels in the environment and on individual behaviour such as use of wireless communication devices (e.g. W-LAN, mobile or cordless phones) and time spent in different microenvironments (Figure 1). For the purpose of estimating exposure, a microenvironment is considered a spatial compartment where an individual spends a certain period of time and exposure can be characterized during that time period. Linkage between behavioural factors and RF-EMF levels in different microenvironments is possible using personal measurements and a time-activity diary. The availability of RF-EMF exposure meters (exposimeters) means that personal RF-EMF exposure to multiple sources in the everyday environment can be more accurately assessed. Several studies have demonstrated the applicability of exposimeter measurements in population samples [13-21]. Comparing exposure levels between countries using data from these first studies is problematic, however, because different types of measurement devices and/or different measurement and analysis procedures have been used. This means that observed differences in exposure measurements may be due to methodological differences and may not reflect real exposure differences between populations. In order to accurately compare exposure levels between or even within countries, it is of crucial importance to conduct comparable measurements. The aim of this paper is to propose basic requirements for the conduct of personal measurement studies based on the current preliminary insights into this topic. This includes descriptions of the study instruments and methodological issues such as selection procedures for study participants, handling of the exposimeter, collection of other relevant data, data handling and reporting of the results.

## Research protocol

### Objectives

Personal measurement studies usually have one of the following two objectives. Firstly, to determine personal exposure distribution in the population of interest (popu-

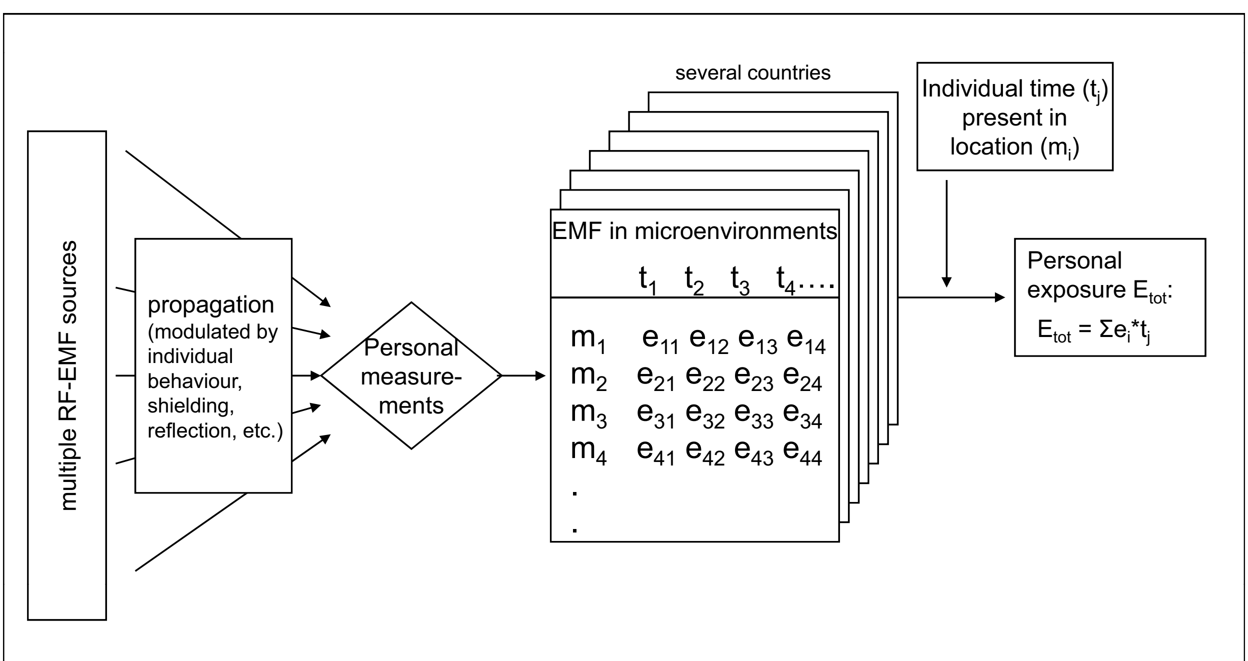


**Figure 1 Personal exposure**. The relation between emissions from RF-EMF, personal measurements, exposure levels ($e_{ij}$) in different microenvironments ($m_i$), time spent at different microenvironments ($t_j$) and personal exposure ($E_{tot}$).

lation survey). Secondly, to characterize typical exposure levels in different microenvironments in the area of interest such as public transportation or outdoor urban areas (microenvironmental measurement). These two objectives should be clearly differentiated because they have major implications for the study methods (Table 1).

## Study instruments

### *Personal exposimeters*

So far two different types of exposimeters have been applied in exposure measurement studies: the EME SPY 120/121 (SATIMO, France) and the ESM-140 (Maschek, Bad Wörishofen, Germany). The latter device is easier to carry, however, measurements of radio FM and TV bands are not possible (Table 2). The EME SPY has an isotropic antenna whereas the ESM-140 takes into account shielding of the body and its antenna is designed in a way that full isotropy is only achieved when the meter is carried on the upper arm, which is a drawback for measurements during the night. Only the EME SPY is suitable for RF-EMF measurements in a stand-alone position. Another disadvantage of the ESM-140 is that accuracy of the differentiation between up- and downlink measurements in the mobile phone bands is limited [17,22]. Recently, SATIMO developed a new type of personal exposimeter (EME YPY 140) with markedly improved characteristics [23]: i.e. increased frequency range (80 MHz-6 GHz), increased dynamic range (sensitivity: 0.005 to 5 V/m), a more appropriate complex signal assessment, a reduced sampling period (from 330 μs to 18 μs) which is relevant for signals with short pulse duration such as DECT and W-LAN, and a reduction of the device's size by a third (Table 2).

Currently, this new device seems to be most appropriate for future measurement studies. Nevertheless, the performance of other exposimeters that may be developed in the future should be thoroughly evaluated as well. Basic requirements for an eligible device are the measurement accuracy, an optimal isotropy, the ability to differentiate between different frequency bands (in particular between up- and downlink in the mobile phone bands) and to be acceptable to study participants. The latter is particularly important for population surveys, as study participants have to agree to carry such a device over a relatively long time period in order to obtain robust measurements of their typical exposure.

### *Geographic Position System (GPS) device*

In addition to the exposimeter, the use of a GPS device that geo-locates the personal RF-EMF measurements is a useful adjunct to exposure studies. This procedure has been successfully applied in the Netherlands [24] and in Belgium [25]. Ideally, such a GPS device should be directly implemented in future exposimeters but has not been so far.

The measured electric field strength can be plotted on a Google Earth map at the latitude, longitude position of

**Table 1: Comparison between a population survey and a microenvironmental measurement campaign.**

| | Population survey | Microenvironmental measurement study |
|---|---|---|
| Unit of observation | Individual | microenvironment* |
| Requirement for the study sample | representative for the population of interest | representative in terms of exposure-relevant behaviours for the population of interest |
| Selection of participants | random and representative sample needed | convenient sample is sufficient oversampling of rare exposure-relevant behaviours |
| Motivation of participants | part of the random sample will not be motivated | convenient sample is more motivated on average |
| diary | basic and simple, if any at all | compulsory |
| Measurement duration | as long as reasonable for the participants | not crucial |
| Sample size | many individuals | many measurements from numerous microenvironments of the same type |

* For the purpose of estimating exposure, a microenvironment is considered a spatial compartment where an individual spends time and exposure can be characterized during that time.

**Table 2: Overview of exposimeters.**

| Band | Frequency [MHz] | Description | ESM-140 | EME SPY 121 | EME SPY 140 |
|---|---|---|---|---|---|
| FM | 88-108 | FM radio broadcasting | no | yes | yes |
| TV3 | 174-223 | TV broadcasting | no | yes | yes |
| Tetrapol | 380-400 | Mobile communication system for closed groups | no | yes | yes |
| TV4/5 | 470-830 | TV broadcasting | no | yes | yes |
| GSM900 uplink | 880-915 | Transmission from handset to base station | yes[1] | yes | yes |
| GSM900 downlink | 925-960 | Transmission from base station to handset | yes[1] | yes | yes |
| GSM1800 uplink | 1710-1785 | Transmission from handset to base station | yes[1] | yes | yes |
| GSM1800 downlink | 1805-1880 | Transmission from base station to handset | yes[1] | yes | yes |
| DECT | 1880-1900 | Digital enhanced cordless telecommunications | yes[1] | yes | yes |
| UMTS uplink | 1920-1980 | Transmission from handset to base station | yes[1] | yes | yes |
| UMTS downlink | 2110-2170 | Transmission from base station to handset | yes[1] | yes | yes |
| W-LAN | 2400-2500 | Wireless Local Area Network | yes | yes | yes |
| WIMAX | 3400-3800 | Worldwide Interoperability for Microwave Access | no | no | yes |
| WI-FI | 5150-5850 | A wireless IEEE 802.11standard | no | no | yes |
| **Other characteristics**: | | | | | |
| Measurement range (V/m) | | | 0.01-70 | 0.05 - 10 | 0.005-5 |
| Measurement cycle | | | 0.5 - 10s | 4 - 255s | 4 - 255s |
| Storage capacity (number of measurements) | | | 260,000 | 12,540 | 80,000[2] |
| Size (L × W × H in mm) | | | 115x45x29 | 193 × 96 × 70 | 169 × 79 × 46 |
| Weight (in g) | | | 87 | 450 | 400 |
| Marker (to register events) | | | yes | yes | yes |

Overview of the exposimeters (ESM-140, EME SPY121) that were previously used in studies and the newly developed EME SPY 140 [23].
[1]combined bands for the frequency range between 880 and 960 MHz and for 1700-2200 MHz.
[2]Theoretical capacity taking into account the capacity of the memory component and the number of bytes to save for measurement, but may not be achieved due to battery life.

the coordinates from the GPS logger. This visualization can be done for all frequency bands and can be used as a quality control tool to check the plausibility of the entries in the time-activity diary (see below). The GPS and exposure data can also be applied as input data for the development of physical or empirical propagation models [26] including spatial characteristics. Also the exposure can be coupled to data from mobile phone network providers for spatial correlation between exposure and the network layout.

#### *Time-activity diary and questionnaire*

In order to obtain interpretable measurements, study participants have to fill in a time-activity diary. The diary will provide additional information about the type of microenvironment experienced by the participants when using the measurement device. The diary needs to be simple and easily comprehensible but also provide standardised information which can be used for data analysis. Thus, there is a certain limitation to what can be achieved in terms of spatial and temporal resolution. In particular, one has to be aware that less demanding tasks can be required from the study participants in a random population sample compared to a convenience sample, which is generally more motivated. For a convenience sample or for hired participants, we propose, as a minimal requirement, that the following microenvironments are considered in all future microenvironmental measurement studies in order to obtain comparable measurements between countries: at home (bed room, living room, other rooms, outside at home [e.g. balcony, garden]), at work, being outdoors (not at home), shopping, driving a car, travelling by public transportation, riding a bicycle, being at bus/train stations, school/universities/courses, or at any other places. If necessary, in a specific geographic context or study objective, the diary may be complemented with additional details of microenvironments. Instead of a paper and pencil diary, use of hand-held computers (personal organizers) may be an option but this has not been done so far in this context and should be piloted.

It is important to note that personal exposimeter measurements do not differentiate between exposure from the participants' equipment (e.g. mobile phone) and other sources for which the distance to the exposimeter may be the same. Such a differentiation is needed from the exposure perspective because the participants' equipment radiates closer to the body causing much more absorption of radiation. Information about participants' own use of equipment that emits RF-EMF should be collected. For exposure to RF-EMF from mobile phones, the best method is to obtain traffic data of the mobile phone from the network operators of study participants during the measurement period. This would still need to be linked to mode of use (hands-free, in-car etc.). Another option is to use information that is stored in the mobile phone. This is not possible for all phone types, however, and generally not for cordless phones. The third option is that study participants note all calls in the time-activity diary or press an event marker of the exposimeter (only available for ESM-140). However, in this case some of the calls may be missed, because the participants forget to note them. Such missing data may not be randomly distributed between study participants or microenvironments and therefore may introduce bias to a study.

In addition to the diary, a questionnaire about other exposure-relevant items and general exposure-relevant behaviour during the measurement period is useful for interpreting the data. Exposure-relevant behaviour relates to the typical use of mobile and cordless phones, use of a hands-free device and the physical location where the phone is kept when such a device is used, use of wireless networks, possible occupational exposures as well as socio-economic variables, housing characteristics and factors that might indicate exposure avoidance behaviour (e.g. concerns about adverse health consequences from electromagnetic fields).

### Study procedures

#### *Measurement duration*

Detailed study procedures depend on the specific aims of a study. Measurement duration for a participant should be at least 24 hours and not exceed 1 week. Short measurement periods may not be representative of the behaviour of the participants (e.g. weekend vs. workday behaviour). Long measurement periods, on the other hand, may result in a decreased diary quality due to participation fatigue. This may be particularly the case in a random population sample because a part of the sample may not be motivated for study participation. Shorter measurement periods make the logistics of exchanging devices more complex. Due to the limited number of measured values that can be stored (e.g. 7168 for the EME SPY 120), the sampling interval is determined by the duration of the measurement period. The optimum sampling interval should be as short as possible and is determined by the duration of the measurement period and the storage capacity of the device. It should also be constant within a given study to facilitate internal comparison. In conclusion, the choice of the measurement duration is not crucial and should be based on logistic and methodological considerations. As a rule, in population surveys, the exposure of interest is that of the individual and the measurement period should be as long as reasonable for participants whereas for microenvironmental measurement studies, a high number of measurements per microenvironment can be obtained with a high sampling rate within a relatively short measurement period.

***Selection of study participants***

In the case of a population survey, the unit of observation is the individual and a randomly selected representative sample of the population is needed to obtain reliable results. For microenvironmental measurements, study participants should be selected in order to represent typical behaviours in different microenvironments.

Participants in a population survey would ideally be selected from population registries. With other recruitment approaches care must be taken to avoid exposure-related selection bias. For instance, people using mobile phones exclusively may be underrepresented in the telephone directory, resulting in an underestimation of mobile phone use in a cohort selected in this way. For population surveys, participation bias is of concern and thus incentives may help to obtain a high participation rate. We also strongly recommend a two-tier recruitment process. First, a short questionnaire should be distributed to the target population with exposure-relevant items including a question as to whether participation in the measurement study is agreed. This needs little effort and the return rate will be probably high. The data can then be used to evaluate how representative the study participants are of the rest of the population in terms of exposure-relevant behaviours and socioeconomic factors.

The sample size that is needed for such a population survey is still difficult to define with the current limited knowledge about the exposure variability in the various populations. Because exposure-relevant behaviour is expected to be related to age, gender, type of residential area (urban, suburban, rural), and time (workday vs. weekend/holidays; day vs. night), we recommend that study participants are selected from predefined strata, thus applying a stratified random sampling. In order to ensure comparability between studies we advise to use the following age groups for analyses: primary school children (depending on the country, about 7-12 years), secondary school children and adolescents (about 13-19 years), young adults (20-35 years), adults (35 up to retirement), and retired people. In total, such a classification results in 30 different strata by age, gender and type of residential area. Future studies may decide not to consider all strata, but if such studies use these predefined strata for selection of study participants and reporting of the measurement results, comparability between studies will be enhanced and exposure differences due to different study sample compositions will not be wrongly attributed to differences between study areas. In order to obtain representative results for the population of interest the following potentially exposure-relevant characteristics or factors should be representatively distributed in each stratum: socioeconomic status, use of wireless communication devices, use of public transport, and day of week. In summary, directly determining population exposure from exposimeter measurements is resource intensive and requires a large study size because the unit of observation is an individual.

Study participant selection criteria are different for microenvironmental measurement studies because the unit of observation is clearly delineated, such as train or outdoor urban residential area. This does not require a random sample but rather study participants who represent the whole range of exposure-relevant behaviours and activities in the area of interest. For instance, children, adolescents and adults behave differently in their daily life and spend their time in different microenvironments (e.g. school vs. workplace). Thus, it is advised to select a few participants from each of the above mentioned strata. A convenience sample of motivated people will help to ensure high compliance with the study protocol. One could even consider hiring study participants who take measurements in predefined microenvironments following a predefined protocol, as in a Dutch measurement study [24]. Because exposimeters can store several thousands of measurements, it is relatively simple to obtain a large amount of measurements per microenvironment. Nevertheless, in order to represent the full range of exposure distributions and behavioural aspects in each type of microenvironment, measurements from numerous participants should be collected for each type of microenvironment. For instance, it is important to have measurements from many different railway stations to obtain a reliable estimate of the general exposure situation in railway stations in a study area.

***Instructions for the study participants***

Handling of the exposimeters affects the measurements and thus the same procedures have to be applied to obtain comparable results from several studies. Ideally, exchange of the measurement devices should take place at the home of the study participants, which would also offer the opportunity for the researcher to take additional objective data about the exposure situation (e.g. spot measurements or data on housing characteristics). Alternatively, participants may collect the instrument at the study centre. In this case one has to be aware that the measurement day does not reflect the typical activity of the study participants, and this should be considered when determining the individual exposure level. In a microenvironmental measurement study one has to ensure that measurements from a specific microenvironment in the vicinity of the study centre are not over-represented in the final data set as this microenvironment may not be representative for all microenvironments of the same type.

An important aspect of obtaining accurate and replicable measurements is the placement of the exposimeter. Based on previous experience we propose that the participants carry the exposimeter in a camera bag in order to keep the position of the device stable. Mobile phones should not be placed in the same bag. A camera bag is impractical when sitting down, and thus in this case the device should be placed in the vicinity of the person. This also minimizes shielding effects by the person which are of concern when the exposimeter is placed on the body [27]. Thereby the participants should be advised not to place the exposimeter at exactly the same place each time and to move it a little bit at least every hour (except during the night) in order to obtain more representative values. When changing the room, participants should carry the exposimeter with them. The exposimeter must not be placed on the floor, on a window sill or in the close vicinity (less than 30 cm) of a wall or of an electrical device.

### *Maintenance and calibration of the exposimeters*

Although exposimeters are calibrated by the manufacturer prior to delivery, it is imperative to conduct further functional tests and calibrations with each device during conduct of the research. Calibration factors may drift with time. Devices may also break down or become corrupt during the course of the study, as participants have to carry them around all the time, presumably resulting in some rough handling. Functional tests should reveal crude deviances from proper functioning and any time shift in the measurement accuracy. Simple functional tests are recommended each time before the device is distributed to a new participant. Basic requirements for functional tests are replicable exposure situations with a transmitter for each frequency band. The absolute measured values of the functional tests are less important than the relative changes between the tests (see Figure 2). A major change in the measurement reading (e.g. >3 dB) indicates that the device may no longer be functioning properly and calls for a thorough investigation, any repairs necessary and re-calibration of the device. Calibration is an extensive procedure because realistic signals have to be used in each frequency band. Continuous wave signals will not produce correct results for pulsed signals [28]. Moreover, isotropy and linearity have to be considered when performing a calibration. There is also a need to take into account that strong signals outside the frequency bands measured by the exposimeters might couple into them or that coupling between adjacent different bands of the exposimeters can occur, e.g. between GSM 1800 downlink and DECT (Table 2). Frequency specific calibration factors have to be determined, i.e. calibration factors might differ within the same frequency band depending on the carrier frequency. This means that different calibration factors can be observed, e.g. at 90 or 100 MHz in the FM band [28]. As a consequence, the calibration factor for each frequency band should take into account the average distribution of the EMF within that band in the study area.

### *Data Management and Cleaning*

Data management includes combining exposimeter data with diary and GIS data. The temporal measurement resolution is usually much denser than the diary resolution and thus cleaning of the dataset is required. Any obvious discrepancies between measurements and diary or GPS data should be resolved. The geo-referenced data allow easy detection of a change of place of the exposimeter. Moreover, the measurement pattern of various frequency bands usually changes abruptly when moving, e.g. going inside from outside or vice versa. Thus, the data should be visually inspected and the plausibility of the diary entries should be checked. Based on experience from previous studies, the most common problem is a time shift between measurements and diary entries, which should be corrected in the diary. An obvious change of the location in the measurement file without a corresponding entry in the diary indicates that a relevant entry in the activity diary has been forgotten. Conversely, a recorded change of location in the diary without a corresponding change in the measurement file indicates that the exposimeter has not been carried on the person. Such measurements or diary entries should be adapted in the most plausible way or removed from the data. All changes should be flagged in the data sheet for later sensitivity analyses. In general, a conservative data cleaning approach is recommended i.e. to change as little as possible. Previous experience suggest that such changes do not have a major impact on the summary statistics of the measurements [15]. Nevertheless, a computerized procedure instead of visual inspection is considered to be more objective and not to introduce systematic differences between studies. Such a procedure has not been developed so far but a common computerized procedure would enhance the reproducibility and reliability of cross-study comparisons.

### *Data analysis*

The main challenge for data analysis is measurements below the detection limit. Although the detection limit is expected to be reduced in future exposimeters, adequate statistical methods must be used to account for subthreshold measurements [29]. For summary statistics we recommend the use of robust regression on order statistics (ROS), which has been shown to produce reliable summary estimates of personal measurements with a substantive proportion of nondetects [30]. Nevertheless, some caution is warranted if only a few and similar values are recorded above the detection limit. In this case, the estimated data distribution produced by ROS is unreli-

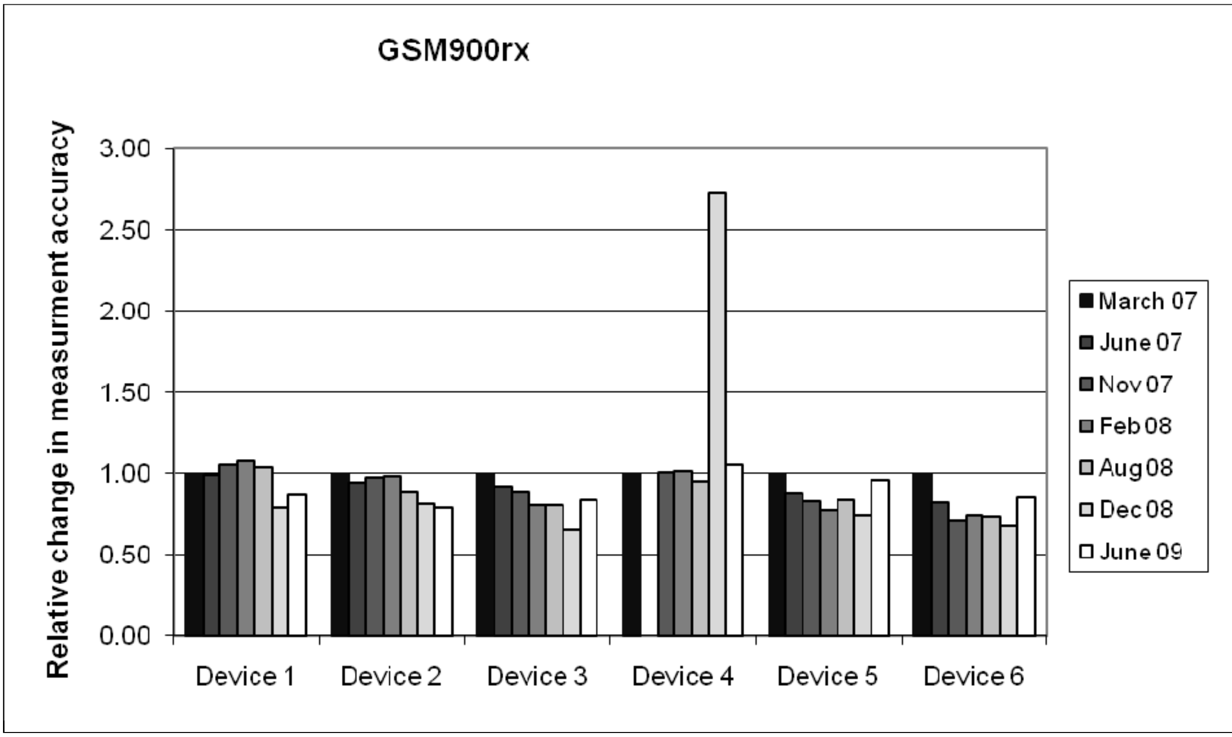


**Figure 2 Functional test of exposimeters**. Example of functional tests of the GSM900 downlink band of the six devices used in a Swiss study (QUALIFEX) conducted by the Federal Office of Metrology in Wabern, Switzerland. All relative changes refer to the V/m units. The tests revealed a problem with device number 4 in December 2008. All other changes were within the measurement uncertainty of ±2 dB.

able. In addition to ROS, a variety of statistical methods for censored data are implemented in the package NADA for the R statistical software [31]. We also recommend regression modelling methods that allow nondetects and non-parametric score tests for censored data, such as the Peto-Peto test.

The presentation of the results depends on the aim of the study: in a population survey the focus is on the distribution of the individual exposure in the study population. This can also be done for microenvironmental studies as shown in Table 3; however, lack of representativeness of the study sample has to be taken into account when interpreting the data. Data distribution includes the average level as well as other exposure metrics potentially relevant for health such as time spent above a certain threshold, rate of change, or other measures reflecting the intrinsic structure of the exposure as done in [32]. Such an analysis does not necessarily require diary data and can also consider different time periods separately such as weekend vs. workday; daytime vs. night (Table 3). In addition, factors that affect individual exposure (e.g. age, gender and use of communication devices) should be analyzed in a population survey using regression modelling. In general, population surveys will be limited for comparing different microenvironments because the diary will provide less detailed information about the activity compared to a microenvironmental measurement study. However, they will directly inform about the distribution of RF-EMF exposure in the population of interest.

In a microenvironmental measurement study the focus of the analysis is the exposure distribution in different microenvironments. Thus, the data for each microenvironment from all study participants can be pooled and subsequently summary statistics can be calculated using robust regression on order statistics. In addition, mean exposure contributions of different RF-EMF sources may be presented to evaluate the importance of different sources in various microenvironments. Such an example is given in Table 4. Note, however, that measurements from the same individual are clustered. Thus, for statistical testing of differences between microenvironments multilevel regression modelling (random effect models) are needed, although, to our knowledge, no such method for censored data is implemented in standard statistical software so far.

In microenvironmental measurement studies it is more challenging to obtain the distribution of individual exposure of the study sample, in particular if one is interested in subgroups. Just averaging the values from a small sam-

**Table 3: Distribution of total (all sources) individual exposure at different places and times in a Swiss study sample (partly reprinted from).**

| | Arithm. mean | Minimum | 5% quantile | 25% quantile | Median | 75% quantile | 95% quantile | Maximum |
|---|---|---|---|---|---|---|---|---|
| **Average (mW/m²)** | 0.134 | 0.014 | 0.030 | 0.054 | 0.092 | 0.163 | 0.351 | 0.881 |
| - Daytime | 0.164 | 0.014 | 0.034 | 0.070 | 0.127 | 0.209 | 0.445 | 1.063 |
| - Nighttime | 0.076 | 0.003 | 0.005 | 0.014 | 0.028 | 0.086 | 0.245 | 1.367 |
| - Workday | 0.134 | 0.013 | 0.027 | 0.055 | 0.096 | 0.170 | 0.353 | 0.776 |
| - Weekend | 0.133 | 0.007 | 0.014 | 0.031 | 0.064 | 0.148 | 0.474 | 1.243 |
| **Time above 1 V/m (%)** | 0.453 | 0.016 | 0.046 | 0.134 | 0.255 | 0.509 | 1.201 | 8.442 |
| - Daytime | 0.629 | 0.000 | 0.038 | 0.174 | 0.359 | 0.697 | 1.988 | 8.754 |
| - Nighttime | 0.083 | 0.000 | 0.000 | 0.000 | 0.000 | 0.072 | 0.313 | 2.101 |
| - Workday | 0.447 | 0.000 | 0.036 | 0.127 | 0.254 | 0.500 | 1.409 | 5.836 |
| - Weekend | 0.458 | 0.000 | 0.000 | 0.052 | 0.157 | 0.365 | 1.714 | 14.958 |
| **Rate of change (mW/m²)[1]** | 0.128 | 0.011 | 0.025 | 0.060 | 0.102 | 0.172 | 0.299 | 0.484 |
| - Daytime | 0.181 | 0.004 | 0.018 | 0.062 | 0.170 | 0.260 | 0.430 | 0.590 |
| - Nighttime | 0.037 | 0.000 | 0.000 | 0.002 | 0.006 | 0.021 | 0.237 | 0.351 |
| - Workday | 0.133 | 0.003 | 0.018 | 0.048 | 0.117 | 0.191 | 0.328 | 0.480 |
| - Weekend | 0.117 | 0.000 | 0.004 | 0.018 | 0.054 | 0.189 | 0.413 | 0.812 |

[1] rate of change $= \sqrt{\frac{\sum_{n}^{i=1}(m_i - m_{i-1})^2}{n-1}}$ ; m = measurement

ple size will produce unstable and unreliable results. In this case, regression models are useful to predict RF-EMF exposure for different population strata. We suggest using a regression model to predict RF-EMF exposure of the population strata suggested above (i.e. gender, age groups, type of residential area, workday vs. weekend, three socioeconomic levels, user of mobile and cordless phones and owning a WLAN at home) although it may not be possible to include all these strata in each future study. Table 5 shows an example of such a predictive regression model. In this case, young female adults living in an urban area, owning a W-LAN, mobile and cordless phones are chosen as the reference group. Their predicted exposure is 0.11 mW/m². By multiplying up the relevant model coefficients, predicted exposure for any population stratum is obtained. For instance: middle aged men living in suburban areas are exposed to 0.13 mW/m² (= 0.11 mW/m²*0.93*1.27). In principle, such models can be built for each frequency band separately. Note that personal predictors are not meaningful if study participants are engaged to carry out a set of specific activities such as walking, shopping, taking a train, etc.

**Table 4: RF measurement mean values for different frequency bands (V/m) according to regression order statistics method (Besançon and Lyon, France, 2005-2006, 377 participants) (reprinted from ).**

| | n° of measurements | FM | Tetrapol | TV 4&5 | GSM Tx | GSM Rx | DCS Tx | DCS Rx | DECT | UMTS Tx | UMTS Rx | WiFi | Total field |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Total** | 2,493,211 | 0.044 | 0.005 | 0.016 | 0.013 | 0.018 | 0.012 | 0.015 | 0.037 | 0.036 | 0.037 | 0.038 | 0.201 |
| **Area** | | | | | | | | | | | | | |
| Besançon | 1,221,716 | 0.052 | 0.001 | 0.016 | 0.011 | 0.014 | 0.006 | 0.011 | 0.032 | 0.045 | 0.050 | 0.052 | 0.201 |
| Lyon | 1,271,495 | 0.036 | 0.008 | 0.016 | 0.016 | 0.022 | 0.018 | 0.020 | 0.041 | 0.020 | 0.034 | 0.020 | 0.202 |
| **Place of residence** | | | | | | | | | | | | | |
| urban | 625,140 | 0.071 | 0.002 | 0.019 | 0.010 | 0.028 | 0.017 | 0.025 | 0.038 | 0.044 | 0.031 | 0.046 | 0.231 |
| periurban | 1,272,213 | 0.039 | 0.008 | 0.015 | 0.014 | 0.016 | 0.011 | 0.014 | 0.038 | 0.038 | 0.040 | 0.037 | 0.201 |
| rural | 595,858 | 0.013 | 0.005 | 0.012 | 0.015 | 0.009 | 0.010 | 0.006 | 0.034 | 0.019 | 0.050 | 0.042 | 0.156 |
| **Time period** | | | | | | | | | | | | | |
| day | 1,657,991 | 0.044 | 0.004 | 0.014 | 0.017 | 0.018 | 0.013 | 0.017 | 0.037 | 0.030 | 0.036 | 0.036 | 0.204 |
| night | 835,220 | 0.045 | 0.040 | 0.026 | 0.006 | 0.018 | 0.010 | 0.012 | 0.037 | 0.050 | 0.043 | 0.040 | 0.197 |
| **Age category** | | | | | | | | | | | | | |
| youths | 727,878 | 0.039 | 0.001 | 0.015 | 0.017 | 0.019 | 0.014 | 0.014 | 0.035 | 0.040 | 0.033 | 0.028 | 0.188 |
| adults | 1,765,333 | 0.047 | 0.007 | 0.016 | 0.012 | 0.018 | 0.011 | 0.016 | 0.038 | 0.037 | 0.039 | 0.042 | 0.206 |
| **Microenvironment** | | | | | | | | | | | | | |
| home | 1,577,162 | 0.045 | 0.008 | 0.022 | 0.010 | 0.017 | 0.010 | 0.012 | 0.041 | 0.044 | 0.044 | 0.037 | 0.200 |
| workplace | 543,868 | 0.047 | 0.005 | 0.014 | 0.014 | 0.017 | 0.014 | 0.021 | 0.030 | 0.025 | 0.040 | 0.043 | 0.205 |
| transportation | 187,699 | 0.044 | 0.005 | 0.012 | 0.030 | 0.027 | 0.024 | 0.024 | 0.025 | 0.027 | 0.033 | 0.040 | 0.215 |
| walk | 37,706 | 0.062 | 0.007 | 0.012 | 0.020 | 0.035 | 0.022 | 0.035 | 0.032 | 0.030 | 0.028 | 0.042 | 0.233 |
| bicycle, motorcycle | 8,310 | 0.044 | 0.023 | 0.019 | 0.023 | 0.035 | 0.027 | 0.029 | 0.026 | 0.070 | 0.029 | 0.040 | 0.227 |
| car | 120,378 | 0.037 | 0.005 | 0.012 | 0.031 | 0.026 | 0.022 | 0.022 | 0.024 | 0.025 | 0.038 | 0.039 | 0.204 |
| bus, tramway | 14,390 | 0.055 | 0.002 | 0.017 | 0.034 | 0.028 | 0.040 | 0.024 | 0.020 | 0.004 | 0.027 | 0.042 | 0.238 |
| train, underground | 6,915 | 0.050 | 0.001 | 0.011 | 0.071 | 0.017 | 0.034 | 0.019 | 0.030 | 0.084 | 0.043 | 0.053 | 0.257 |
| others | 184,482 | 0.036 | 0.007 | 0.008 | 0.021 | 0.025 | 0.018 | 0.016 | 0.028 | 0.012 | 0.024 | 0.033 | 0.192 |

Seasonality and day of the week may be a relevant predictor for personal RF-EMF, although little evidence for this was found in a Swiss study [15]. Nevertheless, these factors may be of importance in other study areas and should be considered. If relevant, they should be included in the data analysis, as a factor in a regression model.

If data about exposure-relevant behaviour are collected, they should be included in the results (e.g. use of mobile phones, W-LAN, etc.). These data may be useful to explain differences between studies and to estimate exposure differences between populations. In addition, secondary data sources can also be used to estimate population exposure taking into account behavioural aspects of the population of interest such as representative survey data on mobile phone use or time spent in public transport.

## Discussion

Newly developed exposimeters allow convenient measuring of personal exposure from multiple sources of RF-EMF in the everyday environment. However, valid comparisons of measurements between studies can only be made if the same basic methods and procedures have been applied. The aim of this paper is to suggest a few key methodological items that should be considered in future studies to enhance the comparability of the results.

The measurement of personal RF-EMF exposure is still a relatively new area of research. Any procedures suggested in this paper are thus still based on somewhat preliminary insights and may be subject to adaptation taking into account results from future studies. Nevertheless, the authors of this manuscript have practical experience from such personal measurements which form the basis

**Table 5: Exposure predictions for different strata.**

| Variable | Category | n | Coefficient | 95%-CI | p-value |
|---|---|---|---|---|---|
| *Age* | young adults (20-34 y) | 56 | reference | - | - |
| | adults (35-64) | 69 | 0.77 | 0.59;1.01 | 0.06 |
| | retired people (>64) | 6 | 0.75 | 0.39;1.42 | 0.37 |
| *Gender* | Female | 74 | reference | - | - |
| | Male | 57 | 0.93 | 0.72;1.20 | 0.58 |
| *Place of residence* | Urban | 76 | reference | - | - |
| | Suburban | 55 | 1.27 | 0.97;1.66 | 0.08 |
| *Ownership of mobile phone* | Yes | 119 | reference | - | - |
| | No | 12 | 0.70 | 0.44;1.11 | 0.13 |
| *Ownership of cordless phone* | Yes | 79 | reference | - | - |
| | No | 52 | 0.91 | 0.68;1.21 | 0.51 |
| *Ownership of W-LAN* | Yes | 50 | reference | - | - |
| | No | 81 | 0.95 | 0.72;1.25 | 0.72 |
| *Socio economic status* | Low | 21 | reference | - | - |
| | Middle | 17 | 0.87 | 0.54;1.39 | 0.55 |
| | High | 93 | 1.10 | 0.77;1.58 | 0.59 |

Coefficients of a multiple loglinear regression model using data from a Swiss RF-EMF population survey [15]. This model allows predicting average RF-EMF exposure in different population strata
Intercept of the model: 0.11 mW/m$^2$ (95%-CI: 0.08-0.17) (exposure during the day of a female person aged 20-34 living in an urban environment, owning a mobile phone, a cordless phone and wireless LAN at home, with the lowest socioeconomic status).
To calculate total exposure of a woman with the same characteristics but who does not own a mobile phone, the value has to be multiplied by 0.70 resulting in an exposure of 0.08 mW/m$^2$. Note that this is only an example to demonstrate the principle of an exposure prediction model. Lack of significance of coefficients for potentially relevant parameters may indicate that a larger sample size is needed for this type of exposure prediction model.

of this presentation of the current state of knowledge for the conduct of personal measurement studies.

We consider it important to clearly differentiate between two objectives that can be achieved by such a study: determination of exposure distribution in a target population (population survey) or measurement of RF-EMF levels in different microenvironments (microenvironmental measurement). Both approaches have their merits and their limitations. A population survey needs a considerable larger sample size than a microenvironmental survey because the unit of observation is an individual. A microenvironmental study allows comparison of the exposure levels between different study areas but does not necessarily reflect population exposure because time spent in different microenvironments may differ between study populations. As an example, studies in France and Switzerland found relatively high RF-EMF levels in trains [15,21] and travelling by train is therefore an exposure-relevant behaviour. Thus, to estimate the importance of this aspect for the RF-EMF exposure of the population, one needs data about the use of trains on the population level. Similarly, exposure of young children, who are not able to carry an exposimeter, can be predicted from their behaviour using measurements of the microenvironments which are relevant for very small children.

We regard our suggestions as basic requirements for future studies. Of course, additional features may be added to this core protocol. For instance, personal measurements of extremely low frequency magnetic fields may be added to the measurement study as has been done in the Netherlands [24]. Another possibility could be to compare geo-referenced personal measurements with the results from propagation models of fixed site transmitters [26] or with spot measurements or to evaluate changes in the exposure situation over a period of a few years.

The conduct of personal measurements is important for several reasons. In the past, mobile phones were a very important source of RF-EMF exposure mainly to the head for everybody who used them [1]. As a consequence most of the human experimental and epidemiological studies focused on mobile phone exposure and did not need personal exposure measurements. However, for future research, a change in exposure patterns can be expected. Firstly, the average output power of new UMTS phones is considerably lower than of GSM phones [33]. Secondly, there is an increasing number of new technologies such as Wireless Local Area Network (W-LAN), Worldwide Interoperability for Microwave Access (WiMax), Radio Frequency Identification (RFID) or Near Field Communication (NFC), contributing to an individual's exposure. Exposure of the general population to these sources is complex and concerns the whole body. Thus, personal exposimeter measurements are useful to better characterize multi-source exposure in the everyday environment.

In principle, one could also use exposimeters in epidemiological studies in order to directly measure individual exposure. However, this approach has several limitations: it is very costly and time-consuming for large studies, and long term measurements are not feasible and need considerable commitment of the study participants which results in a decreased participation rate. Participants might even manipulate the measurements by placing the exposimeter at positions where high RF-EMF exposures are expected. This makes exposimeters unattractive for direct exposure measurements in many epidemiological applications and well-designed personal exposure measurement studies are needed to increase our knowledge about the exposure distribution in the population and its relevant contributors. This facilitates the interpretation of previous RF-EMF research and helps to develop reliable exposure prediction models [34] for future studies. Such reliable exposure assessment methods are urgently needed to conduct epidemiological studies on potential health effects of long-term low dose exposure to RF-EMF in our everyday environment. Although the public is concerned about health risks from this type of exposure, methodologically sound studies are scarce and published studies do not allow firm conclusions to be drawn [35].

Knowledge of the exposure distribution is also needed for health risk assessment and risk communication. In this context it is crucial that study results are representative and comparable, and that exposure differences reflect real differences and are not due to methodological differences. Comparability of exposure measurements is also important for evaluating different approaches to reduce exposure, including environmental measures (e.g. reduced standard limits) and behavioural changes. For instance it will be interesting to evaluate whether exposure from mobile phone base stations in countries with lower standard limits (e.g. Switzerland, Italy) differs from that in the rest of Europe. Differences in standard limits might lead to a different architecture of mobile communication networks, e.g. a higher number of base stations with lower power, leading consequently to different emission patterns.

Exposimeters facilitate the collection of comprehensive data on personal exposure. Personal exposure to various RF-EMF sources can be assessed separately and different types of exposure metrics can be calculated, such as time spent above a certain threshold, rate of change, or other measures reflecting the intrinsic structure of the exposure data, as presented in Table 3. This is important because no biological mechanisms in the low dose range are known yet, hence, it remains unclear which aspects of exposure are relevant for health, if any at all. It has been speculated that effects may be frequency or modulation dependent [36] and, in such a case, estimating average exposure would not be the most appropriate exposure metric.

Exposimeters also have limitations, including the lack of measurement of all sources in the RF-EMF spectrum. At a population level, omitting data on RF-EMF from such sources is not expected to be important, however in specific situations such sources can be relevant, for instance, if someone lives close to a short wave transmitter. Shielding of the body, when carrying the exposimeter, is also a problem. A recent study has estimated that on average the electric field of different frequency bands is underestimated by as much as 64% [27]. In principle, factors could be used to correct the measurements. However, too few investigations in different microenvironments have been made so far for us to feel comfortable in proposing the application of such correction factors at the moment.

The most important limitation of the exposimeter concerns measurements of exposure from mobile phone handsets and other sources that are operated close to the body. In this case the measurement depends on the distance between the emitting device and the exposimeter rather than the distance between the device and the body. Hence, the measurement does not accurately reflect exposure of the body. This could be taken into account by estimating the whole-body $SAR_{wb}$ (Specific Absorption Rate) for each source by taking into account the average field distributions and field propagation for different typical exposure situations and microenvironments as proposed in [25,37]. In doing so, the same measured electric field strength for two frequency bands could mean different $SAR_{wb}$ depending on the typical usage/exposure situation for the corresponding source (e.g. near field from mobile phone vs. far field from mobile phone base station). In this way the exposimeter would extend to a "$SAR_{wb}$-meter" and one could make an analysis in combination with both E-fields and actual whole-body SAR values, enabling future studies to make a comparison of personal exposure with basic restrictions [38]. This is a promising approach and its feasibility should be investigated in future studies.

## Conclusions

In this paper, experiences of various investigators with personal RF-EMF measurement studies are summarized. Based on these experiences criteria for future studies have been developed. Applying such common core procedures in future personal measurement studies is necessary so that observed differences in measurement studies reflect real exposure differences and not merely differences in the methods used.

## List of abbreviations

dB: Decibel; DECT: Digital Enhanced Cordless Telecommunications; EMF: Electromagnetic Field; FM: Frequency Modulated (radio broadcasting); GPS: Geographic Position System; GSM: Global System for Mobile Communications; NFC: Near Field Communication; RF-EMF: Radiofrequency electromagnetic field; RFID: Radio Frequency Identification; ROS: Robust regression on order statistics; $SAR_{wb}$: Whole-body specific absorption rate; UMTS: Universal Mobile Telecommunications System; W-LAN: Wireless Local Area Network; WiMax: Worldwide Interoperability for Microwave Access.

#### Competing interests

The authors declare that they have no competing interests.

#### Authors' contributions

All authors contributed to the methodological discussions. PF conducted the statistical analyses. MR drafted the manuscript with input from all authors. RCP and SM have proofread the manuscript. All authors read and approved the final manuscript.

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# **Article 2:** Persönliche Exposition durch hochfrequente elektromagnetische Felder in der Region Basel (Schweiz): Ein Überblick über die QUALIFEX-Studie

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# Persönliche Exposition durch hochfrequente elektromagnetische Felder in der Region Basel (Schweiz): Ein Überblick über die QUALIFEX-Studie

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**Zusammenfassung**

Im Rahmen der QUALIFEX-Studie wurde bei Anwohnern der Region Basel die individuelle Exposition durch hochfrequente elektromagnetische Felder (HF-EMF) gemessen. Ein Ziel der Studie ist es, die Verteilung der HF-EMF-Exposition in der Bevölkerung zu erfassen und verschiedene Methoden der Expositionserhebung im Hinblick auf ihren Einsatz in epidemiologischen Studien zu evaluieren. Dazu wurden 166 Freiwillige mit tragbaren Exposimetern ausgestattet und ihre Exposition gegenüber HF-EMF während einer Woche gemessen. Zusätzlich wurde ein räumliches Ausbreitungsmodell entwickelt, um die durch ortsfeste Sendeanlagen verursachte Exposition in den Wohnungen der Studienteilnehmenden zu modellieren. In einer zufällig ausgewählten Bevölkerungsstichprobe (n = 1.375) wurden Daten zum Mobil- und Schnurlostelefongebrauch erhoben. Von einem Teil dieser Personen (n = 437) lagen die Mobilfunkverbindungsdaten der vorangehenden 4-6 Monate von den Mobilfunkanbietern vor. Die persönlichen Messungen der 166 Teilnehmenden ergaben eine mittlere HF-EMF Exposition von 0,22 V/m (Bereich: 0,07-0,58 V/m). Die Hauptbeiträge zur Gesamtbelastung stammten von Mobilfunkbasisstationen sowie Mobil- und Schnurlostelefonen. Die mit dem räumlichen Ausbreitungsmodell modellierte HF-EMF Exposition in den Wohnungen der Studienteilnehmenden korrelierte sowohl mit den entsprechenden Messwerten (Rangkorrelation: 0,72) als auch mit der gesamten wöchentlichen mittleren Exposition durch ortsfeste Sender an allen Aufenthaltsstandorten der Teilnehmenden (Rangkorrelation: 0,57). Der selbsteingeschätzte Gebrauch des Mobiltelefons korrelierte mit den Angaben der Netzbetreiber (Rangkorrelation: 0,78). Die QUALIFEX-Studie liefert wichtige Erkenntnisse über die Expositionsverteilung der Bevölkerung und für die Durchführung von epidemiologischen Studien. Um den zukünftigen technischen Entwicklungen Rechnung zu tragen, sollten solche Expositionsmessungen kontinuierlich weiter geführt und gegebenenfalls angepasst werden.

**Schlagwörter:** Epidemiologie, Expositionsabschätzung, hochfrequente elektromagnetische Felder (HF-EMF), Mobilfunk, Modellierung

**Abstract**

**Personal radio frequency electromagnetic field exposure in Basel and area (Switzerland): An overview of the QUALIFEX project**

Within the QUALIFEX project, personal radio frequency electromagnetic field (RF-EMF) exposure was measured. The aim of this publication is to give an overview of the RF-EMF exposure distribution in a Swiss population sample and to evaluate different exposure assessment methods regarding their application in epidemiological studies. Personal RF-EMF exposure of 166 volunteers from Basel, Switzerland, was measured during one week with portable exposure meters. In addition, a geospatial propagation model was developed to predict RF-EMF exposure from fixed site transmitters at study participants' residencies. Self-reported mobile and cordless phone use of a randomly selected population sample (n = 1.375) were collected and for a subsample (n = 437) objective operator data of network providers were available for the previous 4 to 6 months. Mean weekly exposure of all 166 volunteers was 0,22 V/m (range: 0,07-0,58 V/m). Total exposure was mainly due to mobile phone base stations, mobile phone handsets and cordless phones. Predicted exposure at home from the geospatial propagation model correlated with the corresponding measured mean exposure (rank correlation: 0,72) as well as with the measured mean exposure from fixed site transmitters at all places where study participants stayed during one week (rank correlation: 0,57). The rank correlation between self-reported mobile phone use and operator data was 0,78. The QUALIFEX study provides important information on the RF-EMF exposure distribution in the general population and for the conduct of epidemiological studies. With regard to future technical developments, it is important that exposure of the population is monitored continuously and that exposure assessment methods are adapted if necessary.

**Keywords**: epidemiology, exposure assessment, radio frequency electromagnetic field (RF-EMF), personal dosimeter, mobile phone

## 1 Hintergrund

Die zunehmende Nutzung von drahtlosen Kommunikationsmitteln wie Mobiltelefon, Schnurlostelefon oder Wireless LAN (kabelloses Internet) führt bei einem Teil der Bevölkerung zu Besorgnis. Dabei stehen negative Auswirkungen auf das subjektive Wohlbefinden wie Kopfschmerzen oder Schlafstörungen im Vordergrund (Schreier et al. 2006, Schröttner und Leitgeb 2008, Blettner et al. 2009). In zahlreichen wissenschaftlichen Publikationen konnten bisher keine eindeutigen Beweise gefunden werden (Hutter et al. 2006, Berg-Beckhoff et al. 2009), dass hochfrequente elektromagnetische Felder (HF-EMF) die Gesundheit beeinträchtigen, wobei die Datenlage in Bezug auf langfristige alltägliche Expositionen immer noch sehr dürftig ist (Röösli 2008). Eine große Herausforderung bei der Erforschung von solchen langfristigen Auswirkungen ist die Abschätzung der Exposition.

Grundsätzlich können zwei Typen von HF-EMF Quellen unterschieden werden. Zum einen sind dies Quellen, die nahe am Körper (Nahfeld) zur Anwendung kommen und typischerweise vor allem am Kopf hohe, periodische und kurzzeitige Expositionen (z.B. Mobiltelefone) generieren. Zum anderen gibt es Fernfeldquellen, die tiefere, dafür kontinuierliche Ganzkörperexpositionen (z.B. Mobilfunkbasisstationen) verursachen. Neu entwickelte tragbare Dosimeter (Exposimeter) eignen sich für die Erfassung der Exposition im täglichen Leben unter Berücksichtigung, wo sich jemand aufhält. Exposimeter werden typischerweise in der Nähe einer Person deponiert oder unterwegs in einem Rucksack getragen. Sie liefern daher insbesondere aussagekräftige Resultate für quasi-homogene Felder von Fernfeldquellen.

In Bezug auf die Nahfeldquellen sind die Messwerte des Exposimeters jedoch wenig aussagekräftig, da die typische Nutzungsdistanz für diese Geräte viel kleiner ist als die Distanz zum Messgerät. Damit unterschätzen die Exposimetermessungen die Strahlenabsorption des Körpers. Die Exposition am Kopf wird auch bei nur sporadischer Nutzung von Schnurlos- und Mobiltelefonen von diesen Quellen dominiert (Neubauer et al. 2007, Frei et al. 2009, Viel et al. 2009). Entsprechend sind in epidemiologischen Studien Angaben über den Gebrauch von Schnurlos- und Mobiltelefonen für die Abschätzung von Nahfeldexposition nötig. Idealerweise handelt es sich dabei um objektive Daten von Telefongesellschaften. Diese sind aber nicht immer zugänglich, und in manchen Fällen lassen diese Daten nicht automatisch auf den Nutzer schließen (z.B. Geschäftstelefone, Familienanschlüsse), sodass der selbstberichtete Gebrauch auch eine wichtige Rolle bei epidemiologischen Studien spielt (Vrijheid et al. 2009).

Eine weitere Einschränkung des Exposimeters ist, dass bei einer großen Studienpopulation sowohl der zeitliche wie auch der finanzielle Aufwand sehr groß sind. Eine andere Möglichkeit, die Exposition durch Fernfelder abzuschätzen, sind daher räumliche Ausbreitungsmodelle. Bis jetzt gibt es aber erst wenige Ausbreitungsmodelle, die für den Einsatz in epidemiologischen Studien entwickelt wurden (Neitzke et al. 2007, Bürgi et al. 2008). Zudem ist unklar, ob und allenfalls wie stark die modellierte Exposition am Wohnort die Gesamtexposition einer Person im Alltag repräsentiert.

Im Rahmen der QUALIFEX-Studie (Gesundheitsbezogene Lebensqualität und Exposition gegenüber HF-EMF: eine prospektive Kohortenstudie) sammelten wir in einer Bevölkerungsstichprobe in der Region Basel (Schweiz) umfassende Daten zur Expositionssituation, sowohl von Fernfeldquellen wie auch von Nahfeldquellen. Dies beinhaltete persönliche Messungen während einer Woche bei 166 Freiwilligen (Exposimeterstudie), die Entwicklung eines räumlichen Ausbreitungsmodells für ortsfeste Sender (Modellierung) und den Vergleich von selbstberichteter Mobilfunknutzung mit Angaben der Netzbetreiber in einer Zufallsbevölkerungsstichprobe (Hauptstudie). Das Ziel dieser Publikation ist es, einen Überblick über die Expositionssituation einer schweizerischen Bevölkerungsstichprobe zu geben sowie verschiedene Expositionserhebungsmethoden im Hinblick auf den Einsatz in epidemiologischen Studien zu evaluieren.

## 2 Methodik

### 2.1 Persönliche Messungen in der Exposimeterstudie

166 Personen aus der Region Basel (Schweiz) haben für eine Woche ein Exposimeter mit sich herumgetragen und zusätzlich in einem Aktivitätstagebuch die entsprechenden Aufenthaltsorte eingetragen. Die Studienteilnehmenden waren mindestens 18 Jahre alt und wohnten in Basel und der Umgebung. Die Daten wurden zwischen April 2007 und Februar 2008 gesammelt. 131 Studienteilnehmende waren Freiwillige, die sich über unsere Homepage (*www.qualifex.ch*) oder per Telefon angemeldet haben. Die anderen 35 Teilnehmenden wurden aktiv rekrutiert, weil an ihrem Wohnort hohe Expositionen durch Mobilfunkbasisstationen oder durch Radio- und Fernsehstationen zu erwarten waren; entweder aufgrund unseres Ausbreitungsmodells (detaillierter Beschrieb siehe 2.2 "Räumliches Ausbreitungsmodell") oder aufgrund von Kontrollmessungen vom Lufthygieneamt beider Basel (LHA). Weil in einer randomisierten Bevölkerungsstichprobe hoch belastete Personen eher selten sind, haben wir diese hoch belasteten Personen speziell ausgesucht um, möglichst den ganzen Expositionsbereich in unserem Studiengebiet abdecken zu können. Das genaue Auswahlverfahren der Teilnehmenden der Exposimeterstudie ist in Frei et al. (2009) beschrieben. Für eine Validierungsstudie haben 31 Personen das Exposimeter drei bis 41 Wochen nach der Erstmessung während einer zweiten Woche nochmals mit sich herumgetragen.

Für die Messungen der individuellen HF-EMF Exposition wurden sieben Exposimeter EME Spy 120 (SATIMO, Courtaboeuf, France, *http://www.satimo.fr*) verwendet. Das Exposimeter kann in einem Messbereich von 0,05-5 V/m gleichzeitig zwölf verschiedene Frequenzbänder zwischen Radiostation (88–108 MHz) und W-LAN (2,4-2,5 GHz) messen (**Tab. 1**). Das Messintervall des Exposimeters be-

**Tabelle 1:** Verschiedene HF-EMF-Quellen mit deren Frequenzangaben, die mit dem Exposimeter EME Spy 120 gemessen werden können

| Band | Abkürzung | Frequenz (MHz) | Beschreibung |
|---|---|---|---|
| FM | FM | 88-108 | FM Radiosender |
| TV3 | TV | 174-223 | TV Fernsehsender |
| Tetrapol | Tetrapol | 380-400 | Mobiles Kommunikationssystem für Behörden |
| TV4/5 | TV | 470-830 | TV Fernsehsender |
| GSM900 uplink | Mobiltelefon | 880-915 | Übertragung von Mobiltelefon zur Basisstation |
| GSM900 downlink | Mobilfunkbasisstation | 925-960 | Übertragung von Basisstation auf Mobiltelefon |
| GSM1800 uplink | Mobiltelefon | 1710-1785 | Übertragung von Mobiltelefon zur Basisstation |
| GSM1800 downlink | Mobilfunkbasisstation | 1805-1880 | Übertragung von Basisstation auf Mobiltelefon |
| DECT | DECT | 1880-1900 | Schnurlostelefon |
| UMTS uplink | Mobiltelefon | 1920-1980 | Übertragung von Mobiltelefon zur Basisstation |
| UMTS downlink | Mobilfunkbasisstation | 2110-2170 | Übertragung von Basisstation auf Mobiltelefon |
| W-LAN | W-LAN | 2400-2500 | Drahtlose Internetverbindung |
| Total | | | Summe aller Bänder |

trug 90 Sekunden. Das Gerät wurde in einem Rucksack getragen oder für längere Aufenthalte in die Nähe der Person gestellt. Eine Studienassistentin instruierte die Studienteilnehmenden zu Hause und übergab ihnen ein Exposimeter, ein Aktivitätstagebuch und einen Fragebogen mit expositionsrelevanten Fragen. Im Aktivitätstagebuch wurden die Teilnehmenden aufgefordert, ihren Standort auf zehn Minuten genau zu dokumentieren und zusätzlich alle Telefonate mit dem Mobiltelefon und dem Schnurlostelefon ins Tagebuch einzutragen. Im Schlafzimmer jedes Teilnehmenden wurde zudem eine Messung (7-Punktemessung im Raum und 3-Punktmessung vor dem Schlafzimmerfenster) mit dem NARDA SRM-2000 Messgerät durchgeführt. Diese Messung wurde für die Validierung des Ausbreitungsmodells (siehe 2.2 "Räumliches Ausbreitungsmodell") verwendet.

Nach der Datenbereinigung (detailliert beschrieben in Frei et al. (2009)), wurde für jede Person ein wöchentlicher arithmetischer Mittelwert für jedes Frequenzband berechnet. Ein beträchtlicher Anteil der Messungen lag unterhalb der Nachweisgrenze des Gerätes (0,05 V/m). Deshalb erfolgten die Berechnungen der Mittelwerte mit der Methode der "robust regression on order statistics (ROS)" (Röösli et al. 2008). Eigene Telefonate mit dem Mobiltelefon oder dem Schnurlostelefon wurden für die Mittelwertberechnungen ausgeschlossen. Die berechneten Mittelwerte repräsentieren demzufolge primär die Exposition durch HF-EMF Fernfeldquellen.

Die statistischen Analysen wurden mit STATA Version 9.2 und 10.1 (StataCorp. College Station, TX, USA) und R Version 2.7.1 durchgeführt. Alle Berechnungen erfolgten in $mW/m^2$ (Leistungsflussdichte) und wurden danach in V/m umgerechnet.

## 2.2 Räumliches Ausbreitungsmodell

Um die Exposition durch ortsfeste Sender (Mobilfunkbasisstationen und Radio- und Fernsehstationen) am Wohnort der Studienteilnehmenden zu bestimmen, verwendeten wir ein numerisches Ausbreitungsmodell, das detailliert in Bürgi et al. (2008) und (2009) beschrieben ist.

Grundlage für die Modellierung ist eine Datenbank aller Sendeanlagen, welche vom LHA beider Basel erstellt wurde, und welche aus der Mobilfunk-Betriebsdatenbank des Bundesamts für Kommunikation mit den für ein bestimmtes Datum aktuellen Betriebsdaten ergänzt wurde. Ausgehend von diesen Daten (Position und Senderichtung der Antennen, Antennentypen und Abstrahlcharakteristik, mittlere Sendeleistung) berechnet das Ausbreitungsmodell die Stärke des HF-EMF für beliebige Punkte im Raum. Das Modell basiert auf semiempirischen Algorithmen, die ursprünglich für die Radioplanung der Netzbetreiber entwickelt wurden (durch COST und die International Telecommunications Union ITU) und berücksichtigt Schattenwurf und Beugung aufgrund der Topografie und der Bebauung in drei Dimensionen. Das Ausbreitungsmodell für QUALIFEX umfasst die Stadt Basel und den in der Schweiz liegenden Teil ihrer Umgebung (ca. 180 $km^2$ mit ca. 380.000 Einwohnern). Eingabedaten für das Modell sind außer der Antennendatenbank ein digitales Geländemodell und das dreidimensionale Gebäudemodell der Stadt Basel, ergänzt durch ein einfaches Blockmodell für die Gebäude außerhalb der Stadt. Die Software für die Datenhaltung und Berechnung ist die erweiterte Version von NISMap (*www.arias.ch*). Für die Modellierung der HF-EMF im Innern von Gebäuden muss die Dämpfung und Reflexion an der Gebäudehülle und im Innern mitberücksichtigt werden. Da es in der Praxis aber unmöglich ist, die dafür nötigen Materialparameter für ein größeres Gebiet zu erfassen, verwendeten wir als einfachste Näherung einen konstanten mittleren Dämpfungsfaktor von 4,5 dB für alle Gebäude-Außenflächen (Wände, Fenster und Dächer) und einen konstanten Volumendämpfungsfaktor von 0,6 dB/m im Innern. Ausgabedaten des Ausbreitungsmodells sind einerseits farbkodierte Feldstärkekarten, andererseits wurden für die QUALIFEX-Studie gemittelte Feldstärken in der Wohnung der Studienteilnehmenden modelliert (als Mittelwert in einem Kreis von 5 m um ein gegebenes Zentrum, auf einer bestimmten Höhe innerhalb eines Gebäudes).

Das Ausbreitungsmodell wurde anhand der Punktmessungen mit dem NARDA SRM-3000 Messgerät im Schlafzimmer und vor dem Schlafzimmerfenster der Studienteilnehmenden der Exposimeterstudie validiert. Weitere Validierungsmessungen wurden in einer Messkampagne des LHA im Freien 1,5 m über Boden gemacht (Bürgi et al. 2009).

### 2.3 Mobil- und Schnurlostelefongebrauch in der Hauptstudie

Im Mai 2008 begann die Hauptstudie des QUALIFEX-Projekts. 4.000 Fragebögen wurden im Raum Basel (Schweiz) an zufällig ausgewählte Personen zwischen 30 und 60 Jahren verschickt. Der Fragebogen bestand aus verschiedenen Teilen. Es wurden Fragen über den Gesundheitszustand, über die Expositionssituation durch verschiedene Umweltfaktoren (z.B. Luftverschmutzung, Lärmbelästigung etc.) inklusive eigenem Mobiltelefon- und Schnurlostelefongebrauch, soziodemographische Faktoren (Alter, Ausbildung, Zivilstand) sowie Lifestylefaktoren (Rauchen, Größe, Gewicht, körperliche Aktivität) gestellt. Zusätzlich wurden die Teilnehmenden um das schriftliche Einverständnis gebeten, die Verbindungsdaten ihres Mobiltelefongebrauchs der letzten sechs Monate von den jeweiligen Netzbetreibern für statistische Auswertungen benützen zu dürfen. Bei Personen, die dieses Einverständnis gegeben haben, haben wir den selbstberichteten Gebrauch mit den objektiven Daten der Netzbetreiber verglichen.

Wir verglichen die Selbsteinschätzung der Teilnehmenden mit den Verbindungsdaten der Netzbetreiber bezüglich der Dauer des Mobiltelefongebrauchs in Minuten pro Woche. Das 50. und 90. Perzentil wurden benutzt, um die Daten in drei Expositionskategorien einzuteilen. Die Übereinstimmung zwischen den Kategorien wurde mit der linear gewichteten Kappa-Statistik von Cohen abgeschätzt, welche die Höhe der Übereinstimmung zwischen zwei Messgrößen jenseits des Zufalls auf einer Skala von -1 (perfekte Nichtübereinstimmung) und +1 (perfekte Übereinstimmung) misst. Das dazugehörige 95%-Vertrauensintervall (95%-VI) wurde durch Bootstrap mit 5.000 Replikationen berechnet. Die Übereinstimmung auf kontinuierlicher Skala wurde durch den Rangkorrelationskoeffizienten von Spearman quantifiziert.

Von einem der drei Netzbetreiber erhielten wir zusätzlich die Angaben, auf welchem Netz (GSM oder UMTS) die Telefonate durchgeführt wurden und ob es sich dabei um ein UMTS-fähiges Mobiltelefon handelt. Dies zu wissen ist aus der Sicht der Exposition entscheidend, da die mittleren Emissionen von UMTS-Telefonen etwa zwei Größenordnungen kleiner sind als bei GSM-Telefonen (Gati et al. 2009).

Ein Problem bei solchen Vergleichen ist, dass Personen, die angeben, kein Mobiltelefon zu besitzen, folglich keine Einverständniserklärung für einen Datentransfer von einem Mobilfunkbetreiber unterschreiben. Wenn man davon ausgeht, dass solche Personen tatsächlich kaum jemals ein Mobiltelefon benützen, führt der Ausschluss dieser Gruppe zu einer Unterschätzung der Übereinstimmung beim Vergleich der selbstberichteten Daten mit objektiven Daten, da man sich nur auf Mobiltelefonbenutzer konzentriert. Aus diesem Grund wurden alle Analysen zusätzlich unter der Annahme gemacht, dass Teilnehmende, die kein eigenes Mobiltelefon besitzen, eine objektive Mobiltelefongebrauchsdauer von 0 Minuten pro Woche bei den Netzbetreibern aufweisen würden.

## 3 Ergebnisse

### 3.1 Persönliche Messungen in der Exposimeterstudie

Das Durchschnittsalter der Studienteilnehmenden der Exposimeterstudie betrug 42,6 Jahre (**Tab. 2**). 55,4% der Personen waren Frauen.

**Abbildung 1** zeigt die Verteilung der mittleren Exposition der 166 Studienteilnehmenden während einer Woche. Die mittlere Exposition durch HF-EMF ohne eigene Telefonate betrug 0,22 V/m. Die höchste gemessene wöchentliche mittlere Exposition durch HF-EMF eines Studienteilnehmenden war 0,58 V/m. Die kleinste mittlere Exposition lag bei 0,07 V/m.

Der größte Anteil aller Quellen an der Gesamtexposition (aller Studienteilnehmenden zusammen) waren Emissionen von Mobilfunkbasisstationen (32,0%). Das Mobiltelefon und das Schnurlostelefon (29,1% bzw. 22,7%) tru-

**Tabelle 2**: Charakterisierung der Studienpopulation der Exposimeterstudie und der Hauptstudie

| | Exposimeterstudie | | Hauptstudie | |
|---|---|---|---|---|
| | n | % | n | % |
| **Geschlecht** | | | | |
| Männer | 74 | 44,6 | 577 | 42,0 |
| Frauen | 92 | 55,4 | 798 | 58,0 |
| **Alter (Jahre)** | | | | |
| 18–29 | 33 | 19,9 | - | - |
| 30–39 | 39 | 23,5 | 407 | 29,6 |
| 40–49 | 38 | 22,9 | 490 | 35,6 |
| 50–60 | 33 | 19,9 | 478 | 34,8 |
| > 60 | 23 | 13,8 | - | - |
| **Ausbildung** | | | | |
| Keine Ausbildung/Obligatorische Schulzeit | 2 | 1,2 | 89 | 6,5 |
| Berufslehre | 35 | 21,3 | 539 | 39,4 |
| Maturitätsschule | 18 | 11,0 | 124 | 9,1 |
| Höhere Berufsbildung/Universität | 109 | 66,5 | 615 | 45,0 |
| **Distanz Wohnort – nächste Mobilfunkantenne** | | | | |
| Distanz zur nächsten Mobilfunkantenne | 227,5 m | | 278,5 m | |
| **Wohnort** | | | | |
| Basel | 89 | 53,6 | 539 | 39,2 |
| Umgebung von Basel | 77 | 46,4 | 836 | 60,8 |
| **Besitz von kabellosen Kommunikationsmitteln** | | | | |
| Personen mit einem Mobiltelefon | 146 | 88,0 | 1283 | 93,7 |
| Personen mit einem Schnurlostelefon | 128 | 77,1 | 1132 | 82,3 |
| Personen mit Wireless LAN | 55 | 33,1 | 557 | 40,5 |

gen ebenfalls zu einem großen Teil zur Gesamtexposition bei. Die restliche HF-EMF wurde durch die Radio- und Fernsehstation (11,7%), durch Wireless LAN (4,1%) und durch TETRAPOL (0,3%) verursacht.

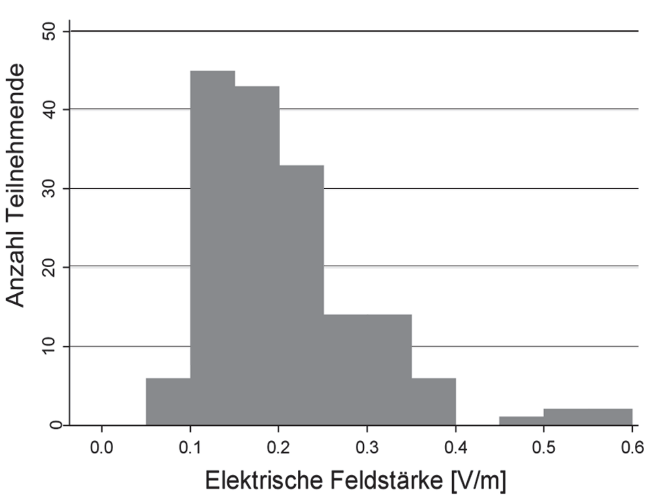


**Abb. 1:** Verteilung der mittleren Exposition (alle Quellen zusammen)

Wie in der Methodik erwähnt, haben wir für die Exposimeterstudie gewisse Personen speziell ausgewählt, weil sie aufgrund ihrer Wohnlage in der Nähe von Mobilfunkbasisstationen oder der Radio- und Fernsehstation speziell belastet sind (27 bzw. 8 Personen). Erwartungsgemäss dominierten bei diesen Personen die entsprechenden Quellen und sie zeigten eine höhere Gesamtexposition durch HF-EMF im Vergleich zu den nicht speziell ausgewählten Studienteilnehmenden (**Abb. 2**). Das nicht speziell ausgewählte Kollektiv (Freiwillige) verkörpert darum eher die durchschnittliche Expositionssituation im Studiengebiet. Bei diesen Personen stammte der Hauptanteil vom Mobiltelefon (39%), gefolgt vom Schnurlostelefon (24%) und von Mobilfunkbasisstationen (22%).

Besitzer eines Mobiltelefons hatten eine höhere Gesamtexposition (0,23 V/m) durch HF-EMF im Vergleich zu Personen, die kein eigenes Mobiltelefon besaßen (0,19 V/m), obwohl bei unseren Auswertungen die eigenen Telefonate nicht berücksichtig wurden. Dasselbe Bild ergab sich bei Personen, die ein Schnurlostelefon hatten (0,24 V/m vs. 0,20 V/m). Bei Personen, die zu Hause ein W-LAN besa-

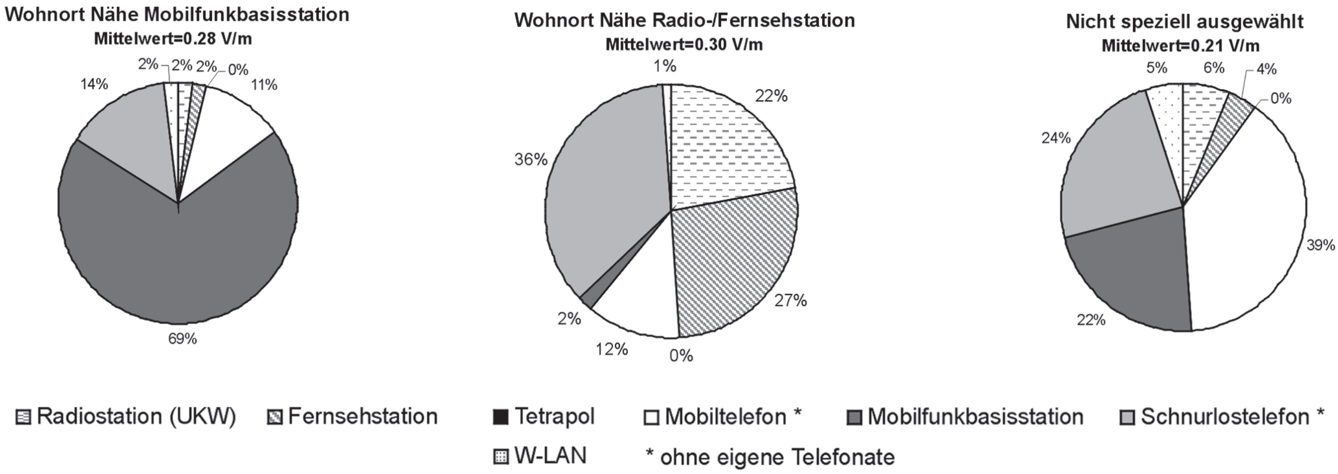


**Abb. 2:** Kuchendiagramme unterschieden nach Rekrutierungsstrategie; Beiträge der verschiedenen Strahlungsquellen in den spezifisch ausgewählten Gruppen (Wohnort Nähe Mobilfunkantenne, n = 27; Wohnort Nähe Radio-/Fernsehstationen, n = 8) und in der nicht speziell ausgewählten Gruppe (n = 131)

ßen, war entsprechend dieser Beitrag höher als für Personen ohne W-LAN (7,7% vs. 2,3%). Im Hinblick auf die Gesamtexposition spielte dieser Unterschied in der Strahlenexposition durch W-LAN aber keine große Rolle (mit W-LAN 0,23 V/m und ohne W-LAN 0,22 V/m) (Frei et al. 2009).

### 3.1.1 Räumliche Variabilität der Exposition

Die höchste mittlere HF-EMF Exposition wurde im Zug gemessen (0,66 V/m). Auch in Straßenbahnen und im Bus (0,37 V/m), während Autofahrten (0,29 V/m) und am Flughafen (0,53 V/m) wurden höhere Expositionen gemessen. Der größte Anteil an der Exposition hatte dabei das Mobiltelefon. Im Zug war 93,5% der Exposition auf das Mobiltelefon zurückzuführen. Relativ geringe mittlere Expositionen wurden in Schulgebäuden (0,09 V/m), in Kirchen (0,15 V/m), in Kinos, im Theater und während Konzerten (0,15 V/m) gemessen. Mobil- und Schnurlostelefone spielten in Schulgebäuden und Kirchen kaum eine Rolle und der Hauptbeitrag war durch Emissionen von Mobilfunkbasisstationen verursacht: 56,0% der Gesamtexposition in Schulhäusern und in Kindergärten und 70,2% in Kirchen.

### 3.1.2 Zeitliche Variabilität der Exposition

Die mittlere Exposition war am Tag (0,25 V/m) höher als in der Nacht (0,17 V/m) was hauptsächlich mit dem vermehrten Gebrauch von Mobiltelefonen anderer Personen zu erklären ist. Die Exposition während der Nacht wurde vor allem durch Mobilfunkbasisstationen (47,2%) verursacht. Es wurden hingegen keine Unterschiede in der mittleren Exposition zwischen den Wochentagen und dem Wochenende (beide 0,22 V/m) festgestellt.

### 3.1.3 Zweitmessungen

Bei 31 Personen wurde nach 3-41 Wochen eine Zweitmessung durchgeführt. Durchschnittlich lag in der zweiten Messwoche die mittlere Exposition tiefer als bei der Erstmessung (Median der Differenzen: -0,08 V/m). Für die Gesamtexposition war die Spearman'sche Rangkorrelation zwischen der ersten und zweiten Wochenmessung 0,61 (95%-KI: 0,32-0,79). Wurden nur die Erst- und Zweitmessungen zu Hause und im Schlafzimmer verglichen, betrug die Korrelation 0,74 (95%-VI: 0,52-0,87), respektive 0,81 (95%-VI: 0,63-0, 91) (Frei, et al. 2009). In **Abbildung 3** sind die Korrelationen der Erst- und Zweitmessungen an verschiedenen Orten dargestellt.

## 3.2 Räumliches Ausbreitungsmodell

Die modellierten Expositionen am Wohnort der Teilnehmenden der Exposimeterstudie variierten über zwei Größenordnungen (ca. 0,02-2 V/m). Die dominierenden Beiträge stammten dabei von GSM 1800 und GSM 900, kleinere Beiträge auch von UKW-Radio, UMTS und Fernsehstationen. Die Validierungsstudie mit den Messwerten des NARDA SRM-3000 Geräts fand für drei verschiedene Orte (Schlafzimmer, vor dem Schlafzimmerfenster, im Freien) Rangkorrelationskoeffizienten zwischen 0,64 und 0,67 (Bürgi et al. 2009).

Für eine Expositionsabschätzung basierend auf Terzilen ergaben sich Kappa-Werte zwischen 0,44 und 0,53. Interessanterweise waren die Resultate für das Modell im Gebäudeinnern (Schlafzimmer) fast gleich gut wie im Freien (Straße, Fenster). Diese Validierungsstudie wurde mit Kurzzeitmessungen unter standardisierten Bedingungen durchgeführt und zeigten, dass das Modell sowohl für Punkte im Freien

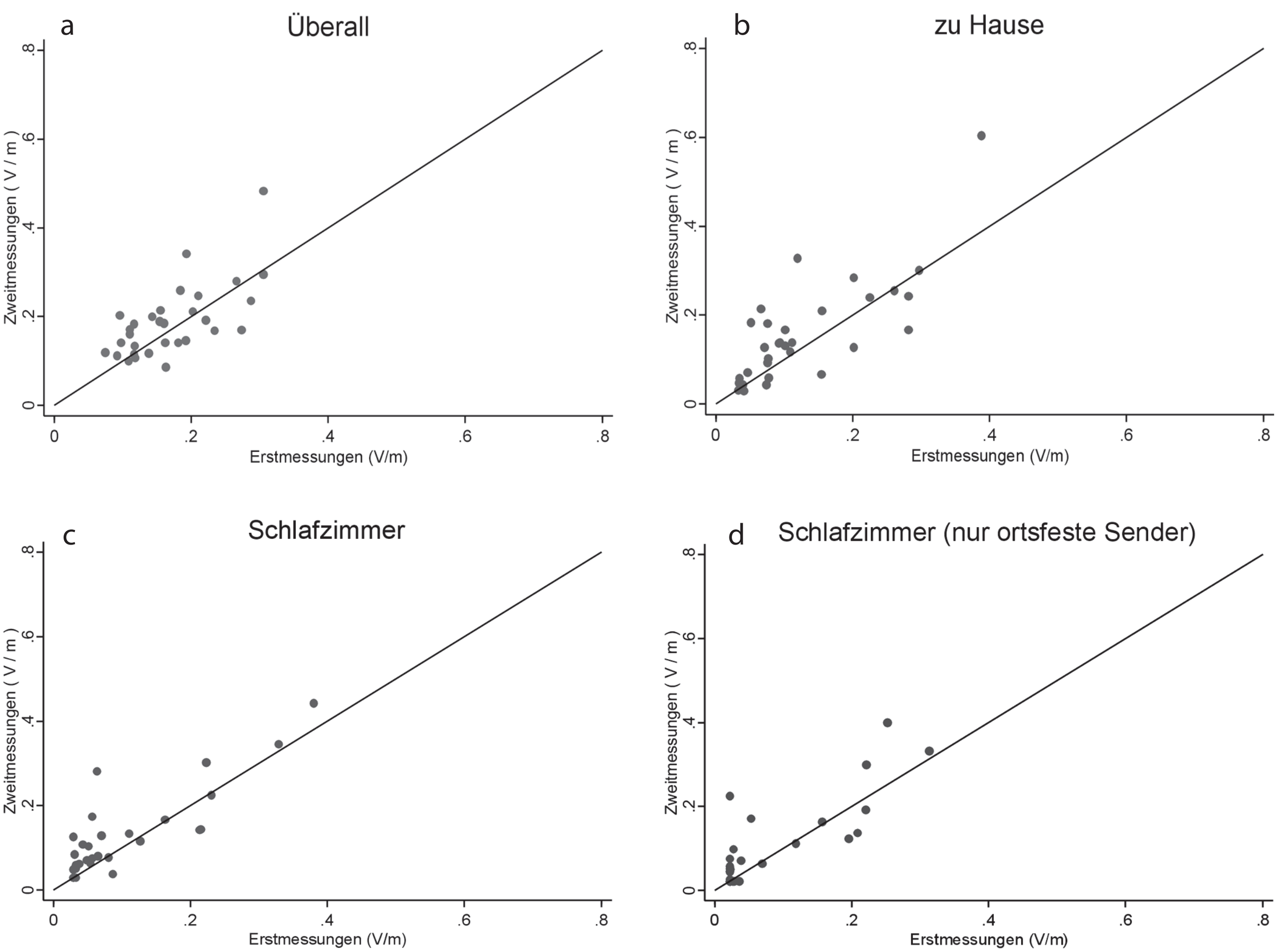


**Abb. 3:** Punktdiagramme der 1. und der 2. Messung in V/m mit der Exposition überall (a), der Exposition zu Hause (b), der Exposition im Schlafzimmer (c) und der Exposition im Schlafzimmer durch ortsfeste Sender (d). Die schwarze Linie markiert Werte der perfekten Übereinstimmung

wie auch für solche im Innern von Gebäuden gültige Resultate liefert. Aus epidemiologischer Sicht besonders interessant ist aber der Vergleich mit den über eine Woche gemittelten Resultaten der Exposimeterstudie. Das zeigt, wie gut die modellierte Exposition am Wohnort die Totalexposition repräsentiert. Dabei zeigt sich, dass die Rangkorrelation und das Kappa ungefähr gleich hoch wie bei der Validierungsstudie sind (**Tab. 3**). Interessanterweise war die Rangkorrelation höher als bei der Validierungsstudie, wenn nur die Exposition durch ortsfeste Anlagen am Wohnort der

**Tabelle 3:** Vergleich zwischen dem modellierten HF-EMF durch ortsfeste Sendeanlagen in der Wohnung der Studienteilnehmenden und verschiedenen Exposimetermessungen (Mittelwerte). $\rho_s$ ist der Spearman-Korrelationskoeffizient, $\kappa_3$ der Kappa-Koeffizierent für eine Klassifikation in drei Terzile. Der Koeffizient $\kappa_{90}$ sowie die Sensitivität und Spezifität wurden für Trennpunkte beim 90. Perzentil berechnet

| | Exposimeter: nur Bänder für ortsfeste Sender | | | Exposimeter: alle Messbänder | | |
|---|---|---|---|---|---|---|
| | Überall | Zu Hause* | Schlafzimmer | Überall | Zu Hause | Schlafzimmer |
| $\rho_s$ | 0,57 | 0,72 | 0,65 | 0,28 | 0,46 | 0,51 |
| $\kappa_3$ | 0,42 | 0,52 | 0,48 | 0,15 | 0,30 | 0,32 |
| $\kappa_{90}$ | 0,52 | 0,65 | 0,38 | 0,45 | 0,45 | 0,38 |
| **Sensitivität** | 0,56 | 0,69 | 0,44 | 0,50 | 0,50 | 0,44 |
| **Spezifität** | 0,95 | 0,97 | 0,94 | 0,95 | 0,95 | 0,94 |

* Man beachte, dass sich nur in dieser Kolonne Messung und Modellierung auf das Gleiche beziehen (Exposition zu Hause durch ortsfeste Sender)

**Tabelle 4:** Vergleich der selbstberichteten durchschnittlichen Dauer des Mobiltelefongebrauchs in Minuten pro Woche mit den Angaben der Netzbetreiber. Zusätzlich sind noch die selbstberichteten Angaben des Gesamtkollektivs bezüglich des Mobiltelefongebrauchs (n = 1.327) und des Gebrauchs von Schnurlostelefonen (n = 1.367) aufgelistet

| | N | Mittelwert (Min./Woche) | Median (Min./Woche) | IQR (Min./Woche) | Maximum (Min./Woche) |
|---|---|---|---|---|---|
| **Gesamtkollektiv** | | | | | |
| Selbstberichtet Mobiltelefongebrauch | 1327 | 67,9 | 13,5 | 55,0 | 1785,0 |
| Selbstberichtet Schnurlostelefongebrauch | 1367 | 75,7 | 21,0 | 105,0 | 560,0 |
| **Mobiltelefongebrauch: Personen mit objektiven Angaben** | | | | | |
| Selbstberichtet | 437 | 61,9 | 13,5 | 35,0 | 1785,0 |
| Netzbetreiber | 437 | 34,0 | 13,4 | 31,7 | 516,3 |
| **Mobiltelefongebrauch: Personen mit objektiven Angaben inkl. Personen die angaben kein Mobiltelefon zu besitzen** | | | | | |
| Selbstberichtet | 524 | 51,6 | 9,0 | 26,0 | 1785,0 |
| Netzbetreiber | 524 | 28,4 | 9,1 | 27,4 | 516,3 |

Studienteilnehmenden ($r_s$=0,72) berücksichtigt wurden. Diese höhere Übereinstimmung im Vergleich mit der Validierungsstudie ist wohl darauf zurückzuführen, dass die Modellierung einen zeitlichen Mittelwert abbildet. Die Kurzzeitmessungen der Validierungsstudie unterliegen aber einer zeitlichen Variabilität, die eine zusätzliche Streuung in den Daten verursacht, die bei den wöchentlichen Exposimetermessungen nicht auftritt.

Selbst bei Berücksichtigung aller Frequenzbänder war die Modellierung mit der persönlichen HF-EMF Exposition korreliert (**Tab. 3**). Die Korrelation zwischen der modellierten Exposition durch ortsfeste Sendeanlagen in der Wohnung im Vergleich zum gemessenen Wochenmittelwert (alle Quellen) betrug 0,28. Entsprechend zeigte die modellierte Exposition eine Sensitivität von 0,5 und eine Spezifität von 0,95 bei einem Trennpunkt beim 90. Perzentil.

### 3.3 Mobil- und Schnurlostelefongebrauch in der Hauptstudie

Von den 1.375 retournierten Fragebögen der Hauptstudie haben 1.327 Personen Angaben über ihren Mobiltelefongebrauch und 1.367 Personen Angaben über ihren Schnurlostelefongebrauch gemacht. Für 437 Teilnehmende waren sowohl die Selbsteinschätzung des Mobil- und Schnurlostelefongebrauchs vom Fragebogen als auch die Mobilfunkverbindungsdaten von den Netzbetreibern vorhanden.

Die Teilnehmenden der Hauptstudie gaben im Durchschnitt an 67,9 Minuten pro Woche mit einem Mobiltelefon zu telefonieren und 7,5 Minuten länger mit einem Schnurlostelefon (**Tab. 4**). Der durchschnittliche selbstberichtete Mobiltelefongebrauch von den 437 Personen mit Netzbetreiberdaten war 61,9 Minuten verglichen mit 34,0 Minuten gemäß Netzbetreiber. Hingegen unterschied sich die mediane Anzahl Minuten Mobiltelefongebrauch pro Woche kaum zwischen Selbsteinschätzung und den Angaben der Netzbetreiber. Dieses Resultat ändert sich nicht, wenn man Personen mit einschließt, die angaben, kein Mobiltelefon zu besitzen. Der Kappa-Koeffizient zwischen selbsteingeschätztem wöchentlichen Mobiltelefongebrauch und Netzbetreiberangaben war 0,41 (95%-VI: 0,33-0,49, n = 437). Der entsprechende Rangkorrelationskoeffizient betrug 0,63 (95%-VI: 0,57-0,68, n = 437) (**Abb. 4**). Schließt

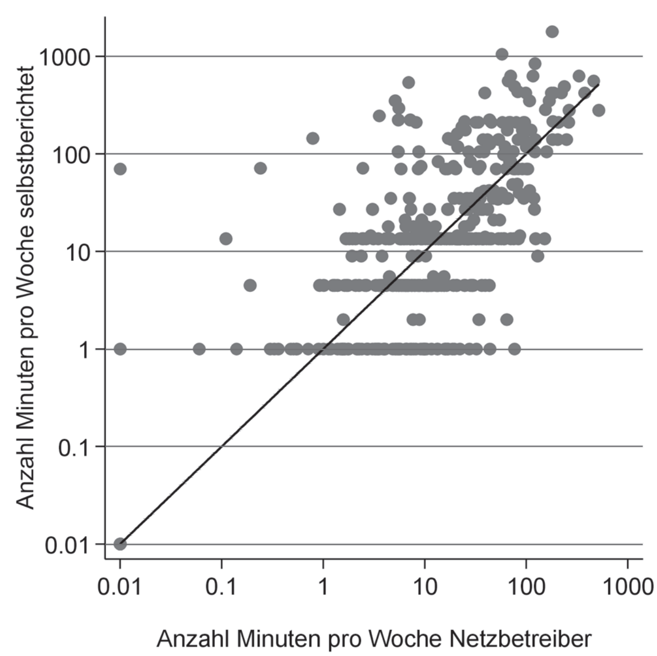


**Abb. 4:** Streudiagramm der logarithmierten wöchentlichen Dauer des Mobiltelefongebrauchs in Minuten pro Woche selbsteingeschätzt und Angaben der Netzbetreiber. Die schwarze Linie markiert Werte der perfekten Übereinstimmung (n = 524). (Werte von 0 wurden mit 0,01 ersetzt, um den Logarithmus berechnen zu können)

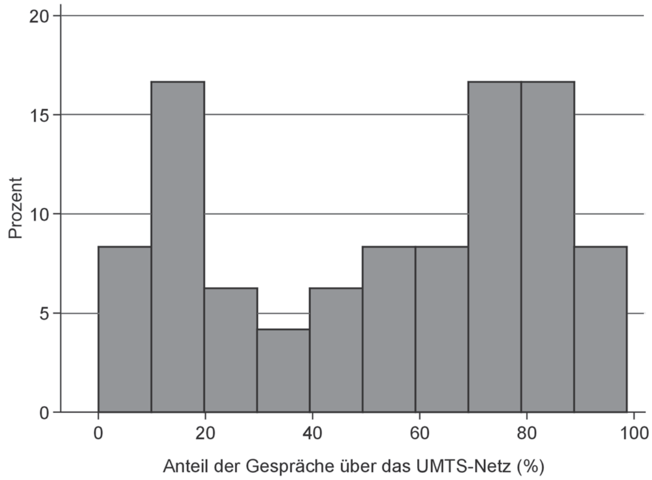


**Abb. 5:** Prozentsatz der privaten Gespräche, die bei einem bestimmten Anteil über das UMTS-Netz geführt wurden (n = 47)

man diejenigen Personen ein, die angaben, kein Mobiltelefon zu benutzen, erhöhte sich die Übereinstimmung (Kappa = 0,51, 95 %-VI: 0,45-0,58, n = 524) und der Rangkorrelationskoeffizient von 0,78 (95 %-VI: 0,75-0,81, n = 524).

Insgesamt gaben 179 (13,0%) Teilnehmende der Hauptstudie an, ein UMTS-Telefon zu besitzen. 928 (67,5%) Teilnehmende gaben an, kein UMTS-Telefon zu besitzen und 268 (19,5%) gaben an, es nicht zu wissen. Die Übereinstimmung zwischen der Selbsteinschätzung, ob man ein UMTS-fähiges Mobiltelefon besitzt und den entsprechenden Angaben der Mobilfunkbetreiber, war in einer Untergruppe, wo wir die entsprechenden objektiven Angaben hatten, moderat (Kappa = 0,44, 95 %-VI: 0,27-0,61, n = 207). So hatten nur 17 von 31 Personen, die angaben ein UMTS-Telefon zu besitzen, tatsächlich ein solches Telefon benutzt. Interessanterweise erfolgten auch bei einem UMTS-fähigen Mobiltelefon längst nicht alle Gespräche über das UMTS-Netz, obwohl die Benutzung von UMTS beim entsprechenden Netzbetreiber zum Studienzeitpunkt priorisiert wurde (**Abb. 5**).

## 4 Diskussion

Ziel dieser Publikation war es, die Exposition durch HF-EMF bei einer Bevölkerungsstichprobe in der Region Basel zu charakterisieren sowie verschiedene Expositionserfassungsmethoden zu evaluieren. Die totale gemessene mittlere Exposition durch alle HF-EMF Quellen lag in unserer Stichprobe bei 0,22 V/m. Am meisten trugen Emissionen von Mobilfunkbasisstationen, von Mobiltelefonen und von Schnurlostelefonen zur Gesamtexposition bei. Das räumliche HF-EMF-Ausbreitungsmodell zeigte eine gute Übereinstimmung mit den Punktmessungen des NARDA SMR-3000 und den Exposimetermessungen und korrelierte sogar mit der gesamten wöchentlichen Exposition der Studienteilnehmenden.

Unsere Messkampagne hat gezeigt, dass die mittlere totale Exposition deutlich geringer ist als die von der ICNIRP empfohlenen Grenzwerte (ICNIRP 1998). Beim Vergleich mit den Grenzwerten ist aber zu beachten, dass sich die Grenzwerte auf zeitliche und örtliche Maxima beziehen, während wir mit dem Exposimeter Durchschnittswerte erhoben haben. Dies gilt auch für die speziell ausgewählten Personen, die in der Nähe von Mobilfunkbasisstationen oder Radio-/Fernsehstationen wohnen. Unsere Resultate sind im Allgemeinen vergleichbar mit anderen Studien. So haben Viel et al. (2009) eine ähnliche mittlere Exposition mit demselben Gerätetyp und einer ähnlichen statistischen Methode (robust regression on order statistics) in einem Studienkollektiv von 377 zufällig ausgewählten Personen in Frankreich gemessen. Dort betrug die mittlere Exposition 0,201 V/m. Berechnen wir die mittlere Exposition von denjenigen Personen in der Exposimeterstudie, die wir nicht speziell ausgewählt haben (n = 131), so ergibt sich eine praktisch identische mittlere Exposition (0,204 V/m). Die höchsten Expositionen wurden in der französischen Studie durch das Schnurlostelefon, das W-LAN und die Radiosender gemessen. In unserer Studie war die Exposition vor allem durch Schnurlostelefone, Mobilfunkbasisstationen und Mobiltelefone dominiert. Dies ist insofern interessant, als dass die Schweizer Anlagegrenzwerte für Emissionen von Mobilfunkbasisstationen tiefer sind als die ICNIRP-Referenzgrenzwerte, die in Frankreich gelten. Von daher hätte man eher erwartet, dass der Anteil von Mobilfunkbasisstationsstrahlung in Frankreich größer ist als in der Schweiz. Dies war aber nicht der Fall. Bei uns war die mittlere Exposition durch Basisstationen beim unselektierten Kollektiv 0,096 V/m, in der französischen Zufallsstichprobe 0,044 V/m. Es stellt sich also die Frage, ob ein dichteres Mobilfunkbasisstationsnetz zu höheren mittleren Expositionen führt, oder ob diese Unterschiede auf andere Gründe zurückzuführen sind. Auch bei Thomas et al. (2008) lag die mittlere Exposition weit unter den ICNRIP-Grenzwerten. Die mittlere Exposition lag dabei zwischen 0,13% und 0,58% der ICNIRP-Grenzwerte. Allerdings mussten die Nachtmessungen aus den Analysen ausgeschlossen werden und es wurden nur drei Frequenzbereiche gemessen: GSM900, GSM1800 (inkl. UMTS und DECT) und W-LAN.

Auffällig bei unseren Resultaten ist der hohe Expositionsbeitrag durch Mobiltelefone (39% bei den nicht-selektierten Probanden), obwohl wir Messungen von der Analyse ausgeschlossen haben, wenn im Tagebuch vermerkt war, dass selber telefoniert wurde. Somit repräsentieren diese Messungen entweder Telefonate benachbarter Personen, organisatorische Kommunikation des eigenen Mobiltelefons (z.B. Übergabe der Kommunikation zwischen zwei Basisstationen bei Zellenwechsel) oder es handelt sich um eigene Telefonate, die nicht im Tagebuch notiert wurden. Aufgrund unserer Daten lässt sich nicht bestimmen, wie groß die jeweiligen Anteile sind. Sollte sich jedoch bestätigen, dass ein substanzieller Beitrag der persönlichen HF-EMF-Exposition von Mobiltelefonen benachbarter Personen stammt, wäre dies vergleichbar mit der Situation beim Rauchen bzw. Passivrauchen. Natürlich sind die Gesundheitsimplikationen beim heutigen Kenntnisstand für Rauchen und HF-EMF-Strahlung deutlich unterschiedlich.

Im Hinblick auf zukünftige epidemiologische Forschung konnten durch diese verschiedenen Expositionsabschätzungsmethoden wichtige Erkenntnisse gewonnen werden:

Erstens zeigte sich, dass es möglich ist, mithilfe von Exposimeter und Aktivitätstagebuch wertvolle Daten über die Expositionssituation der Bevölkerung zu sammeln. Es zeigte sich aber auch, dass solche Messungen hohe Ansprüche an die Studienteilnehmenden stellen und eine hohe Motivation voraussetzen. Das bedeutet, dass die direkte Anwendung zur Expositionsabschätzung in epidemiologischen Studien limitiert ist, da bei einer Zufallsbevölkerungsstichprobe wohl ein erheblicher Teil der Personen die Teilnahme verweigern würde. Das hätte einen Selektionsbias zur Folge, wenn die Verweigerung abhängig vom Gesundheitszustand und der Exposition ist. Zudem ist zu beachten, dass bei der direkten Expositionsabschätzung mit dem Exposimeter, die Messungen einfach manipuliert werden können, indem man das Messgerät absichtlich in die Nähe von HF-EMF-Quellen stellt. Aus diesem Grund wurden in der QUALIFEX-Studie die Expositionserhebungen in einem separaten Kollektiv durchgeführt. Die Teilnehmenden der Exposimeterstudie hatten also keine Motivation die Messergebnisse zu beeinflussen.

Eine zweite wichtige Erkenntnis der Studie war, dass sich die mittlere persönliche HF-EMF-Exposition während einer Woche auch Monate später mit einer Zweitmessung noch reproduzieren lässt. Das war nicht a priori zu erwarten, da HF-EMF in der Umwelt eine große zeitliche und räumliche Heterogenität aufweisen. Der Grund für die Reproduzierbarkeit liegt in erster Linie darin, dass die Expositionssituation am Wohnort entscheidend zur durchschnittlichen Exposition beiträgt. Es scheint, dass im Alltag alle Personen ähnlich exponiert sind, aber die Exposition am Wohnort entscheidend zwischen hoch und tief Exponierten diskriminiert. Zu Hause verbringt man einen großen Teil seiner Zeit und die Expositionssituation bleibt relativ konstant. Da diese erheblich von den Emissionen von ortsfesten Sendeanlagen beeinflusst ist, erklärt sich auch, warum die Sensitivität und Spezifität der Expositionsmodellierung von ortsfesten Sendeanlagen mit dem Ausbreitungsmodell sich praktisch nicht verändern, wenn man es mit der gemessenen Totalexposition von allen Quellen vergleicht (**Tab. 3**).

Drittens konnte die Studie damit zeigen, dass sich die Exposition durch ortsfeste Sender am Wohnort modellieren lässt und sogar mit der mittleren gemessenen HF-EMF-Exposition während einer Woche über alle Frequenzen korreliert. Das bedeutet, dass im Prinzip alleine mit einem solchen Modell gewisse Expositionsdiskriminierungen möglich sind. Natürlich ist der Fehler in der Expositionsabschätzung größer als bei einer Expositionsabschätzung, die zusätzliche individuelle expositionsrelevante Aspekte mitberücksichtigt, wie beispielsweise den Besitz eines Schnurlostelefons (Frei et al. 2009). Dafür erfordert eine Modellierung keine Teilnahmebereitschaft von Studienteilnehmenden, sodass von dieser Seite bei einer epidemiologischen Studie kein Selektionsbias zu erwarten ist. Zusätzlich kann mit einem Modell mit wenig Zusatzaufwand die Exposition für ein deutlich größeres Studienkollektiv modelliert werden und es ist auch möglich historische Exposition oder Langzeitexpositionen abzuschätzen, wenn die entsprechenden Inputdaten vorliegen. In einer bereits publizierten Studie von Neitzke et al. (2007) wurde auch ein Ausbreitungsmodell für eine epidemiologische Studie entwickelt. In dieser Studie konnten nur Daten von Mobilfunkbasisstationen (keine Daten von Radio- und Fernsehstationen) als Inputdaten verwendet werden. Dieses Modell wurde danach in einer epidemiologischen Studie angewendet (Breckenkamp et al. 2008). Dabei hat sich gezeigt, dass die Qualität und Präzision der Inputdaten sehr wichtig ist. Diese Erkenntnis bestätigen auch unsere Ergebnisse (Bürgi et al. 2009).

Viertens zeigte sich, dass die Übereinstimmung von selbstberichteter Mobilfunknutzung und objektiven Netzbetreiberangaben relativ gut war. Dennoch stellt sich die Frage, ob bei epidemiologischen Studien der Fehler zufällig verteilt ist oder abhängig vom Gesundheitsstatus ist. Im Rahmen dieser Studie lässt sich das nicht bestimmen. Falls Letzteres zutrifft, ist ein Bias bei der Analyse der Expositions-Wirkungsbeziehung zu erwarten. Falls Kranke ihren Gebrauch überschätzen, würde ein falsch-positives Resultat resultieren; bei Unterschätzung ein falsch-protektiver Effekt. Im Hinblick auf zukünftige Studien kommt erschwerend dazu, dass viele Leute nicht wissen, ob sie ein UMTS-Telefon besitzen. Und sogar falls bekannt, ist unklar, wie häufig tatsächlich auf dem UMTS-Netz telefoniert wird.

Mit den Expositionsmessungen im Rahmen der QUALIFEX-Studie konnten wichtige Erkenntnisse über die Expositionssituation der Bevölkerung gewonnen werden. Insgesamt lässt sich feststellen, dass immer noch sehr wenig über die typische Exposition der Allgemeinbevölkerung im Alltag bekannt ist. Bisherige Messkampagnen fokussierten häufig auf Orte, wo hohe Messwerte zu erwarten sind und haben nicht berücksichtigt, wo und wie lange sich Personen typischerweise aufhalten. Ein besseres Verständnis der Exposition der Allgemeinbevölkerung erlaubt eine effizientere Planung zukünftiger epidemiologischer Studien, eine bessere Interpretation der Ergebnisse der bisherigen Studien und bildet die Grundlage für Risikoabschätzung auf Populationsebene. Es ist aber auch zu berücksichtigen, dass alle diese Erkenntnisse vorübergehender Natur sind. Die technische Entwicklung ist rasch und dies wird die Expositionssituation der Bevölkerung verändern. Aus diesem Grund ist es wichtig, dass Expositionsmessungen und Modellierungen kontinuierlich weiter geführt und gegebenenfalls den neuen Umständen angepasst werden.

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# 4 RF-EMF AND SLEEP

# **Article 3:** Effects of everyday radiofrequency electromagnetic field exposure on sleep quality: a cross-sectional study

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# Effects of Everyday Radiofrequency Electromagnetic-Field Exposure on Sleep Quality: A Cross-Sectional Study

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**Mohler, E., Frei, P., Braun-Fahrländer, C., Fröhlich, J., Neubauer, G., Röösli, M. and the Qualiflex Team. Effects of Everyday Radiofrequency Electromagnetic-Field Exposure on Sleep Quality: A Cross-Sectional Study. *Radiat. Res.* 174, 347–356 (2010).**

**The aim of this cross-sectional study was to investigate the association between exposure to various sources of radiofrequency electromagnetic fields (RF EMFs) in the everyday environment and sleep quality, which is a common public health concern. We assessed self-reported sleep disturbances and daytime sleepiness in a random population sample of 1,375 inhabitants from the area of Basel, Switzerland. Exposure to environmental far-field RF EMFs was predicted for each individual using a prediction model that had been developed and validated previously. Self-reported cordless and mobile phone use as well as objective mobile phone operator data for the previous 6 months were also considered in the analyses. In multivariable regression models, adjusted for relevant confounders, no associations between environmental far-field RF EMF exposure and sleep disturbances or excessive daytime sleepiness were observed. The 10% most exposed participants had an estimated risk for sleep disturbances of 1.11 (95% CI: 0.50 to 2.44) and for excessive daytime sleepiness of 0.58 (95% CI: 0.31 to 1.05). Neither mobile phone use nor cordless phone use was associated with decreased sleep quality. The results of this large cross-sectional study did not indicate an impairment of subjective sleep quality due to exposure from various sources of RF EMFs in everyday life** 

## INTRODUCTION

The possible effects of radiofrequency electromagnetic-field (RF EMF) exposure on health-related quality of life are of public health concern (*1–3*). The most often reported complaints related to RF EMFs are impairments of sleep quality (*4, 5*).

Several studies investigated the effect of short-term RF EMF exposure on sleep measures in a laboratory setting, applying real and sham exposure randomly under well-controlled exposure conditions (*6–8*). Objective sleep measures derived from electroencephalography (EEG) were used in these laboratory studies. Overall, these studies showed no consistent association between RF EMF exposure and objective sleep measures (i.e. sleep architecture), but small differences for different frequency ranges in the EEG were observed repeatedly after exposure to RF EMFs. The primary aim of laboratory studies is to identify a possible biological mechanism of the effect of RF EMF exposure on sleep, if any exists. In general, laboratory studies are conducted with a relatively small number of participants and therefore have limited statistical power to investigate subjective sleep quality. Moreover, the unfamiliar environment of a sleep laboratory may prevent detection of subtle effects of RF EMFs on sleep quality, as has been reported by several individuals.

Epidemiological studies allow the examination of the association between RF EMFs and subjective sleep quality in a large population sample. The main challenge is to perform an appropriate exposure assessment. Until now, only a few studies were conducted. In early studies, associations between RF EMF exposure and subjective well-being or sleep quality were observed (*9, 10*). However, in these studies, simple exposure proxies like self-reported distance to mobile phone base stations were used, which have been demonstrated to be inadequate (*11, 12*). Information bias was also of concern in these studies and might have influenced the results. Additionally, selection bias might affect results in such cross-sectional studies if participation is related to both health and exposure status (*13, 14*). More recent studies on RF EMF exposure and sleep quality used spot measurements in the bedroom for exposure classification (*15, 16*). No differences in sleep quality (Pittsburgh Sleep Quality Index) or in other health outcomes (headache, SF-36 and health complaint list) were observed between individuals with high and low exposures. Although more sophisticated exposure assessment methods were used in these studies, it still is not

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clear how well such spot measurements represent long-term exposure to various sources of RF EMFs in our everyday environment. For these reasons, in our study, we used personal RF EMF exposure measurements and modeling of fixed-site transmitters (e.g. mobile phone base stations and broadcast transmitter) to develop a method to assess individual exposure (*17*).

Due to the unknown biological mechanism, it is unclear which aspect of exposure is relevant for sleep disturbances, if there are any. It is conceivable that exposure at the head, caused mainly by mobile and cordless phones, is most relevant (close to body sources). Alternatively, environmental sources like exposure from mobile phone base stations or broadcast transmitter, which in general cause lower but continuous whole-body exposures, might play a role (far-field environmental RF EMF exposure). RF EMF exposure might cause symptoms immediately, or the accumulated radiation might be more important. Additionally, psychological aspects appear to be important. Previous studies showed that subjective well-being and sleep quality can be impaired in people from concern or expectations if they think they are highly exposed to various sources of RF EMFs (*3*) (also called a nocebo effect).

The primary aim of this cross-sectional study was to evaluate whether environmental RF EMF exposure is associated with self-reported sleep quality. We also evaluated whether sleep quality is affected by other RF EMF exposure surrogates such as night exposure or use of mobile or cordless phones.

## METHODS

In May 2008, 4000 questionnaires entitled ''environment and health'' were sent out to people aged between 30 to 60 years who were randomly selected from the population registries of the city of Basel (Switzerland) and from five communities in the surroundings of Basel. To minimize noneligibility due to language difficulties, only Swiss residents or people living in Switzerland for at least 5 years were selected. A reminder letter was sent out 3 weeks after the first invitation for participation. Nonresponders were contacted by phone 6 to 10 weeks after the first questionnaires were sent out, and they were asked a few key questions. Ethical approval for the study was received from the Ethical Commission of Basel on March 19, 2007 (EK: 38/07).

### *Written Questionnaire*

The questionnaire addressed three issues: (1) sleep quality and general health status; (2) exposure-relevant characteristics and behaviors (*17*) such as owning a mobile phone, a cordless phone, and/or a wireless LAN and duration of cordless phone use and mobile phone use; and (3) socio-demographic factors such as age, gender, education, marital status and additional confounders like body mass index (BMI), physical activity, smoking behaviors and alcohol consumption.

### *Excessive Daytime Sleepiness and Self-Reported Sleep Disturbances*

To assess subjective sleep quality, we used two sleep outcomes. Daytime sleepiness was determined by the Epworth Sleepiness Scale (ESS), which assigns values ranging from 0 (no daytime sleepiness) to 21 (very excessive daytime sleepiness) (*18*). We calculated the ESS scores and created a new binary variable according to a previous study on insomnia indicating excessive daytime sleepiness (ESS score over 10) (*19*).

General subjective sleep quality was assessed by using four standardized questions from the Swiss Health Survey 2007 (*20*). The four questions on subjective sleep quality in the Swiss Health Survey asked about the frequency of difficulty in falling asleep, fitful sleep, waking phases during night, and waking up too early in the morning using a four-point Likert scale with categories ''never'', ''rare'', ''sometimes'' and ''most of the time''. Out of these four questions, a binary sleep quality score (SQS) was calculated by adding up all items (ranging from 0 to 12) and defining a score of eight as having sleep disturbances (*20*).

### *Exposure Assessment*

Our main hypothesis was that environmental whole-body exposure in everyday life may affect sleep quality. We developed a model for predicting personal exposure to environmental RF EMFs on the power flux density scale in mw/m$^2$ (*17*) in which we measured personal RF EMF exposure of 166 volunteers from our study area by means of a portable EME Spy 120 exposure meter. Volunteers carried the exposimeter and filled in an activity diary for 1 week (*21*). The exposimeter measured 12 different frequency bands of RF EMFs ranging from FM radio (frequency modulation; 88–108 MHz), TV (television, 174–223 MHz and 470–830 MHz), Tetrapol (terrestrial trunked radio police; 380–400 MHz), uplink in three frequency ranges (communication from mobile phone handset to base station; 880–915, 1710–1785, 1920–1980 MHz), downlink in three frequency ranges (communication from mobile phone base station to handset; 925–960, 1805–1880, 2110–2170 MHz), DECT (digital enhanced cordless telecommunications; 1880–1900 MHz), and W-LAN (wireless local area network; 2400–2500 MHz). In addition, we developed a three-dimensional geospatial propagation model in which the average RF EMF from fixed-site transmitters (e.g., mobile phone base stations and broadcast transmitters) was modeled for the study region (in- and outside of buildings) (*22, 23*). Based on this geospatial propagation model and on data from the exposimeter measurements, the relevance of potential predictors on exposure was examined in multivariable non-linear regression models. The following exposure-relevant factors were identified and included in the prediction model for environmental exposure in everyday life (*17*): owning a mobile phone, owning a wireless LAN at home, having the DECT base station in the bedroom, having a cordless phone at the place where one spends the most of their time during the day, house characteristics (window frame and type of house wall), hours per week in public transport and cars, percentage full-time equivalent spent at an external workplace, and exposure from fixed-site transmitters at home computed by the geospatial propagation model (*22, 23*).

To estimate exposure during the night, a separate night prediction model was developed. Ownership of a cordless phone base station in the bedroom, wireless LAN in the bedroom, house characteristics (type of house wall and window frame), and the modeled value of fixed-site transmitters were included in this specific prediction model.

We used the above-mentioned geospatial propagation model for modeling exposure from fixed-site transmitters at home (*22*) in mW/m$^2$ as well as in percentage of the ICNIRP (International Commission on Non-Ionizing Radiation Protection) (*24*) reference level according to method of Thomas *et al.* (*28*).

Finally, with respect to local exposure to the head, we used self-reported use of mobile and cordless phones per week as reported in the written questionnaire. Informed consent was also sought from participants to obtain operator data for their mobile phone use for the last 6 months from the three Swiss mobile phone network operators.

*Sensitivity Analysis*

To evaluate a nocebo effect and information bias (which is also of concern in this area of research), we asked participants about their subjective exposure. They had to estimate their exposure compared to the Swiss population and to indicate whether they felt they were equally, less or more exposed in comparison to the average of the Swiss population. Geo-coded data were available for all study participants. This allowed us to calculate the distance from their residence to the next mobile phone base station as an additional exposure surrogate.

*Nonresponder Analyses*

To evaluate the extent of potential selection bias in our study, nonresponder interviews were conducted to gather information on general health status, socio-demographic factors and exposure-relevant behaviors and factors. One month after the reminder letter was sent out, we tried to contact all nonresponders. Information on age, gender and geo-coded addresses was available for all 4000 persons.

We calculated "selection bias factors" for different exposure proxies (i.e., owning a mobile phone, a cordless phone and/or a W-LAN and distance to the next mobile phone base station) using the Greenland method (*25*) as was done by Vrijheid *et al.* (*26*). For these calculations we assumed that data from nonresponder phone interviews are representative for all nonresponders. Dividing the observed odds ratio by the bias factor yields the correct unbiased association between exposure and outcome. A bias factor of 1.0 indicates that there is no bias.

*Statistical Analyses*

For binary outcomes (ESS score and SQS), logistic regression models with three groups of exposure levels for all exposure proxies (<50th percentile, 50th to 90th percentile, >90th percentile) were performed. Mean average RF EMF exposures were calculated in $mW/m^2$ and converted to V/m. In addition, linear regression models were computed using the continuous score of both sleep scales. Separate analyses were done for each of the four questions of the Swiss Health Survey.

The models were adjusted for age, sex, body mass index (BMI), stress perception, physical activity, smoking habits, alcohol consumption, self-reported disturbance due to noise, living in urban or suburban areas, belief in health effects due to RF EMF exposure, education and marital status. Use of mobile and cordless phones was included in all models as an independent exposure measure. Missing values in the confounder variables were replaced with values of either the most common category (categorical variables) or with the mean value (linear variables) to ensure that all analyses were performed with an identical data set for the ESS and the SQS, respectively. Most missing values in confounder variables were observed in self-reported disturbance of noise [33 missing out of 1212 observations (2.7%)]. Stratified analyses and testing for interaction were done for people reporting as electrohypersensitive (EHS). We defined EHS individuals as those reporting as "electrohypersensitive" or those reporting adverse effects due to RF EMFs.

All statistical analyses were carried out using STATA 10.1 (StataCorp, College Station, TX).

## RESULTS

### *Study Participants*

Of the 4000 persons participating in the study, 237 were excluded due to noneligibility because of severe disabilities ($n$ = 27), death ($n$ = 1), incorrect addresses ($n$ = 36), absence during study time ($n$ = 73), or language problems ($n$ = 100). A total of 1375 people completed the questionnaire. Detailed information on the response rate is illustrated in Fig. 1. Users of sleeping pills ($n$ = 81) as well as night shift workers ($n$ = 82) were excluded from all the analyses. The final analyses thus included 1212 participants. Due to missing values in exposure variables (mobile phone and cordless phone use) and in sleep quality scores (ESS and SQS), 1129 study participants remained for the analyses of excessive daytime sleepiness and 1163 study participants remained for the analyses of self-reported sleep disturbances. Characteristics of all study participants are listed in Table 1. The mean age (standard deviation) of study participants was 46 (± 9) years, and 39% of all responders lived in the city of Basel. There were more female (58%) than male participants. Ninety percent reported that they had a good or very good health status, which was comparable to the general Swiss population (87%).[2] The majority was married (60%) and of normal weight (BMI <25) (62%).

Seventy-eight percent of the study participants reported that they believed that there are people who develop adverse health effects due to RF EMF exposure, 18.2% assigned their own adverse health effects as being due to RE EMF exposure, and 8.1% reported that they were "electrohypersensitive". Due to overlapping, 20.9% of our study population was electrohypersensitive according to our definition.

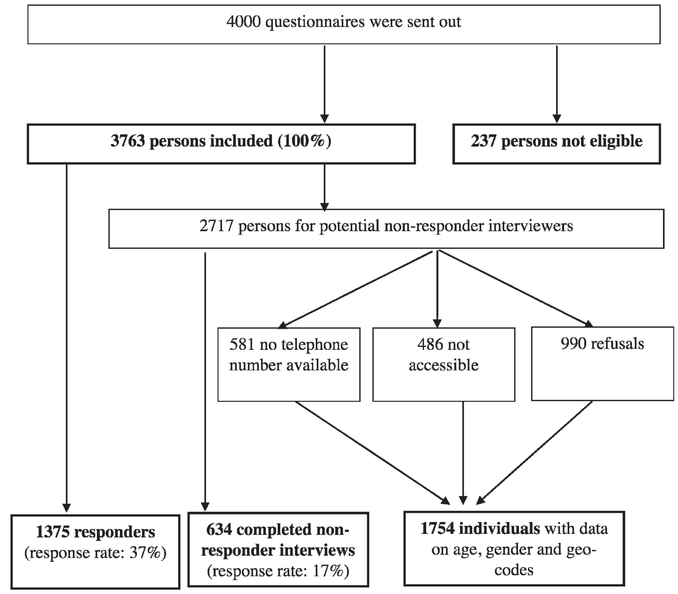


**FIG. 1.** Schematic illustration of the study design and response rate.

[2] National Statistical Institute (Switzerland) 2007; http://www.bfs.admin.ch/bfs/portal/de/index/themen/14/02/01/key/01.html.

**TABLE 1**
**Characteristics and Results of Statistical Comparison of all Study Participants (including nonresponders)**

| | Participants ($n$ = 1212)[a] | *Percent* | Nonresponders ($n$ = 2388) | *Percent* | *P* value |
|---|---|---|---|---|---|
| Age (years) | | | | | 0.05 |
| 30–40 | 319 | *26* | 719 | *30* | |
| 41–50 | 421 | *35* | 829 | *35* | |
| 51–60 | 472 | *39* | 840 | *35* | |
| Sex | | | | | <0.05 |
| Female | 706 | *58* | 1190 | *50* | |
| Male | 506 | *42* | 1198 | *50* | |
| Distance to the next mobile phone base station (percentage closer than 50 m) | 45 | *4* | 165 | *7* | <0.05 |
| Health status[b,c] | | | | | <0.05 |
| Very good | 445 | *37* | 215 | *34* | |
| Good | 636 | *53* | 302 | *48* | |
| Half-half | 107 | *9* | 86 | *14* | |
| Bad | 12 | *1* | 18 | *3* | |
| Very bad | 3 | *0* | 8 | *1* | |
| Educational level[b,c] | | | | | 0.171 |
| None | 79 | *7* | 56 | *9* | |
| Apprenticeship | 591 | *49* | 320 | *51* | |
| Higher education/University | 542 | *45* | 255 | *40* | |
| Owning a mobile phone[b,c] | | | | | <0.05 |
| Yes | 1049 | *87* | 572 | *90* | |
| No | 163 | *13* | 60 | *10* | |
| Owning a cordless phone[b,c] | | | | | 0.176 |
| Yes | 994 | *82* | 537 | *85* | |
| No | 213 | *18* | 96 | *15* | |
| Owning wireless LAN[b,c] | | | | | 0.931 |
| Yes | 492 | *41* | 259 | *41* | |
| No | 709 | *59* | 370 | *59* | |

[a] After exclusion of nightshift workers ($n$ = 82) and users of sleeping drugs ($n$ = 81).
[b] Nonresponder data only for a subsample of 634 nonresponders who answered a short nonresponder interview by phone (numbers in nonresponder analyses can vary due to missing data).
[c] Data may not sum up to 100% due to missing data.

### *Level of Exposure*

The predicted everyday life mean and median exposure was 0.18 V/m for all the included study participants. The cut-off point for 90th percentile was 0.21 V/m. The maximum predicted value was 0.33 V/m. The mean predicted exposure during the night was 0.06 V/m (median: 0.02 V/m, cut-off 90th percentile: 0.09 V/m, maximum: 0.33 V/m), and the mean exposure through fixed-site transmitters (geospatial propagation model) was 0.08 V/m (median: 0.04 V/m, cut-off 90th percentile: 0.12 V/m, maximum: 0.62 V/m). The mean level of exposure from fixed-site transmitters was 0.15% of the ICNIRP reference level. On average, study participants reported using their mobile phones 62.8 min per week and their cordless phones 75.1 min per week. Informed consent for objective data on mobile phone use from the network operators was obtained from 470 study participants. Those who gave informed consent reported that they used their mobile phone 46.5 min per week, while the operator data showed a mobile phone use of 28.8 min per week (*27*). The Spearman rank correlation was 0.76 (95% CI: 0.71–0.83) for self-reported mobile phone use and the operator data.

The majority (64%) of the participants estimated that their exposure was similar to the average for the Swiss population, while 29% believed they were less exposed and 7% believed they were more exposed.

### *Excessive Daytime Sleepiness (ESS score)*

The prevalence of excessive daytime sleepiness (ESS score > 10) was 29.5%. The results of the logistic regression models for crude and adjusted odds ratios (OR) are presented in Table 2. No statistically significant association between excessive daytime sleepiness and various exposure surrogates was observed. The analysis showed a tendency toward excessive daytime sleepiness for the highest-exposed group through fixed-site transmitters, although it was not statistically significant. This finding was confirmed when exposure

**TABLE 2**
**Association between Excessive Daytime Sleepiness (Epworth Sleepiness Scale) and Different Exposure Surrogates [odds ratios (OR) and 95% CI of the three exposure categories]**

| | Exposure categories | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | < 50th percentile | | 50th–90th percentile | | | > 90th percentile | | |
| Excessive daytime sleepiness ($n$ = 1129) | No. of cases[a] | OR | No. of cases[a] | OR | 95% CI | No. of cases[a] | OR | 95% CI |
| Far-field exposure | | | | | | | | |
| Everyday life exposure | | | | | | | | |
| Crude | 180 | 1.00 | 153 | 1.10 | (0.84–1.43) | 25 | 0.77 | (0.47–1.24) |
| Adjusted[b] | 180 | 1.00 | 153 | 1.14 | (0.83–1.57) | 25 | 0.58 | (0.31–1.05) |
| Exposure during night | | | | | | | | |
| Crude | 174 | 1.00 | 149 | 1.14 | (0.87–1.48) | 35 | 1.06 | (0.68–1.65) |
| Adjusted[b] | 174 | 1.00 | 149 | 1.05 | (0.76–1.43) | 35 | 1.21 | (0.74–1.98) |
| Exposure through fixed-site transmitters | | | | | | | | |
| Crude | 170 | 1.00 | 142 | 1.07 | (0.82–1.40) | 46 | 1.86 | (1.21–2.85) |
| Adjusted[b] | 170 | 1.00 | 142 | 1.02 | (0.74–1.39) | 46 | 1.52 | (0.93–2.50) |
| Close-to-body exposure | | | | | | | | |
| Mobile phone use (self-reported) | | | | | | | | |
| Crude | 210 | 1.00 | 106 | 1.18 | (0.89–1.57) | 32 | 1.05 | (0.69–1.64) |
| Adjusted[b] | 210 | 1.00 | 106 | 1.24 | (0.91–1.70) | 32 | 1.03 | (0.62–1.69) |
| Mobile phone use (operator data)[c] | | | | | | | | |
| Crude | 65 | 1.00 | 152 | 1.11 | (0.72–1.70) | 14 | 1.26 | (0.63–2.54) |
| Adjusted[b] | 65 | 1.00 | 152 | 1.30 | (0.82–2.07) | 14 | 0.91 | (0.39–2.11) |
| Cordless phone use (self-reported) | | | | | | | | |
| Crude | 178 | 1.00 | 165 | 1.27 | (0.98–1.65) | 13 | 1.44 | (0.71–2.90) |
| Adjusted[b] | 178 | 1.00 | 165 | 1.30 | (0.99–1.72) | 13 | 1.65 | (0.72–3.50) |

[a] Indicates number of people in the corresponding exposure group with an Epworth sleepiness score over 10.
[b] Adjusted for age, body mass index, sex, physical activity, alcohol consumption, smoking habits, stress perception, urban/suburban, marital status, educational level, noise perception, belief in health effects due to radiofrequency electromagnetic-field exposure.
[c] For a subsample of 453 subjects who consented to obtain data from the operator.

was calculated as a percentage of the ICNIRP reference level (adjusted OR for the 90th percentile: 1.62; 95% CI: 0.99–2.64). Similar results were found for linear regression models (data not shown).

Based on interaction tests, we found no indication that RF EMF exposure affects EHS individuals differently than non-EHS individuals ($P > 0.05$ for all exposure surrogates).

### *Self-Reported Sleep Disturbances (SQS)*

Problematic sleep disturbances were reported by 9.8% of respondents. There was no evidence that having sleep disturbances was influenced by everyday life exposure, exposure through fixed-site transmitters or exposure during the night (Table 3). The OR for the top decile of exposed individuals according to the percentage of the ICNIRP reference value was 0.95 (95% CI: 0.47 to 1.90). Mobile phone and cordless phone use showed no statistically significant effects on having sleep disturbances, but tendencies toward fewer sleep disturbances with increased use of a mobile phone could be seen in the logistic (Table 3) and linear regression models (data not shown). However, analysis of a subsample with objective mobile phone operator data did not show such a tendency (Table 3).

The separate analyses of each item on the sleep quality score (falling asleep, fitful sleep, waking phases during night, waking up early in the morning) revealed no exposure–response association (data not shown). Interaction tests and stratified analyses for EHS and non-EHS individuals showed no difference between the two subgroups.

### *Sensitivity Analysis*

An association between self-reported sleep quality and self-estimated exposure could indicate the presence of information bias or a nocebo effect, or rather the development of symptoms due to concerns. In our study, we found some indications for the presence of a nocebo effect (Table 4). People reporting to be less exposed to mobile phone base stations in comparison to the average population are less likely to suffer from excessive daytime sleepiness (Table 4). Correspondingly, people who lived closer than 50 m to the closest mobile phone base station had a higher risk for excessive daytime sleepiness, although it was not statistically significant. Self-reported sleep disturbances were increased in people claiming to be more exposed in comparison to the average population. These trends were most pronounced for self-estimated exposure to a mobile phone base

**TABLE 3**
**Association between Self-Reported Sleep Disturbances (Sleep Quality Score) and Different Exposure Surrogates [odds ratios (OR) and 95% CI of the three exposure categories]**

| | Exposure categories | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | < 50th percentile | | 50th–90th percentile | | | > 90th percentile | | |
| Self-reported sleep disturbances ($n$ = 1163) | No. of cases[a] | OR | No. of cases[a] | OR | 95% CI | No. of cases[a] | OR | 95% CI |
| Far-field exposure | | | | | | | | |
| Everyday life exposure | | | | | | | | |
| Crude | 98 | 1.00 | 68 | 0.91 | (0.65–1.28) | 14 | 0.87 | (0.48–1.60) |
| Adjusted[b] | 98 | 1.00 | 68 | 1.11 | (0.72–1.70) | 14 | 1.11 | (0.50–2.44) |
| Exposure during night | | | | | | | | |
| Crude | 88 | 1.00 | 76 | 1.14 | (0.81–1.50) | 16 | 1.01 | (0.57–1.80) |
| Adjusted[b] | 88 | 1.00 | 76 | 1.30 | (0.85–1.98) | 16 | 1.29 | (0.66–2.53) |
| Exposure through fixed-site transmitters | | | | | | | | |
| Crude | 88 | 1.00 | 77 | 1.15 | (0.82–1.62) | 15 | 0.94 | (0.52–1.69) |
| Adjusted[b] | 88 | 1.00 | 77 | 1.16 | (0.76–1.75) | 15 | 1.09 | (0.53–2.22) |
| Close-to-body exposure | | | | | | | | |
| Mobile phone use (self-reported) | | | | | | | | |
| Crude | 124 | 1.00 | 41 | 0.71 | (0.49–1.05) | 13 | 0.71 | (0.38–1.30) |
| Adjusted[b] | 124 | 1.00 | 41 | 0.67 | (0.43–1.02) | 13 | 0.64 | (0.31–1.28) |
| Mobile phone use (operator data)[c] | | | | | | | | |
| Crude | 42 | 1.00 | 30 | 0.91 | (0.54–1.51) | 5 | 0.60 | (0.22–1.62) |
| Adjusted[b] | 42 | 1.00 | 30 | 1.57 | (0.89–2.78) | 5 | 1.03 | (0.32–3.30) |
| Cordless phone use (self-reported) | | | | | | | | |
| Crude | 102 | 1.00 | 66 | 0.80 | (0.57–1.12) | 8 | 1.51 | (0.67–3.40) |
| Adjusted[b] | 102 | 1.00 | 66 | 0.71 | (0.49–1.03) | 8 | 1.11 | (0.44–2.78) |

[a] Indicates number of people in the corresponding exposure group with a sleep quality score over 8.
[b] Adjusted for age, body mass index, sex, physical activity, alcohol consumption, smoking habits, stress perception, urban/suburban, marital status, educational level, noise perception, belief in health effects due to radiofrequency electromagnetic-field exposure.
[c] For a subsample of 453 subjects who consented to obtain data from the operator.

station. Subjective exposure was not correlated to modeled mobile phone base station radiation (Spearman correlation coefficient: –0.01) or total everyday life exposure (Spearman correlation coefficient: 0.13).

### *Nonresponder Analysis*

To evaluate a possible selection bias, we compared responders of the questionnaire with nonresponders. The nonresponder analyses, comparing all 1212 participants included in our analyses with the 2388 nonresponders, showed small differences between study participants and nonresponders (Table 1). Nonresponders were generally younger, and the participation rate for women was higher than for men. The distance between the closest mobile phone base station and place of residence was smaller for the responders. Some of the nonresponder information was available only for the nonresponders who participated in the telephone interviews ($n$ = 634): Participants in these telephone interviews were more likely to be an owner of a mobile phone (90%) than full study participants (87%). Study participants who filled in the questionnaire were somewhat healthier than nonresponders. No difference was observed in educational level in owning a wireless LAN or cordless phone. The prevalence of nonresponders (telephone interviews) who reported that they were "electrohypersensitive" was 16%. In the full study only 8% answered yes to the corresponding question ($P < 0.0001$).

In our selection bias factor, we found a bias factor of 0.79 for owning a mobile phone, 0.70 for owning a cordless phone, 0.95 for owning a W-LAN, and 1.33 for living within 50 m from a mobile phone base station. Thus we expect that in our study the exposure–response association for mobile and cordless phone use tends to be biased downward whereas the exposure–response association for fixed-site transmitter tends to be biased upward.

## DISCUSSION

The aim of this study was to investigate the association between various RF EMF exposure surrogates and self-reported sleep quality. Neither everyday-life environmental RF EMF exposure nor exposure during night through fixed-site transmitters or from mobile and cordless phones was associated with excessive daytime sleepiness or with having sleep disturbances. We found some indication for nocebo effects and information bias; this means that persons who assumed that they were exposed more than the average for the Swiss population reported that they suffered more often, although not statistically significantly, from sleep disturbances than participants who felt that they were equally exposed as the average of the Swiss population.

*Strengths*

Our study is based on a large sample size. To our knowledge, our study used the most comprehensive exposure assessment method to date by considering exposure-relevant behavior and characteristics (prediction model) as well as modeling RF EMFs from fixed-site transmitters with a geospatial model (*22*). All relevant exposure sources of everyday life were included in the prediction model, and the feasibility and reproducibility of this exposure assessment method could be demonstrated (*17*). Using prediction models for exposure assessment instead of conducting spot or personal measurements, as has been done in other studies (*15, 16, 28*), is time- and cost-saving for large study populations and is expected to better represent all sources of RF EMF exposure in everyday life.

We included several exposure surrogates in our study. This allowed us to check for consistency and biological plausibility, because no biological mechanism has been established. In particular, we included both close-to-body sources and far-field sources. In addition to self-reported mobile phone use, we considered objective operator data on mobile phone use for a subsample who gave consent.

*Limitations*

The cross-sectional study design is one of our main limitations, in particular with respect to EHS individuals. EHS individuals may tend to avoid known sources of RF EMF exposure and are therefore expected to be less exposed. If so, a cross-sectional study, where outcome and exposure are measured at the same time, could not capture an increased risk. It could even result in observation of a protective effect from exposure (although this was not the case in our study). Conversely, people who did not attribute their own symptoms to EMF exposure were not expected to avoid exposure sources. Thus our cross-sectional study should reveal an association in nonhypersensitive individuals, if one is present, because RF EMF exposure is relatively constant over a few months (*21*). This means that present exposure is also representative of exposure a few months before. In this regard, it is also relevant that self-estimated exposure actually is not correlated to true exposure. This indicates that most persons are not aware of their most relevant exposure sources. Unawareness of the exposure status implies that information bias is unlikely in our study.

In our study, we did not take polysomnographic sleep measures. We were mainly interested in self-reported data on sleep quality and well-being, because a decrease in self-perceived sleep quality due to RF EMF exposure is the most often stated concern of the population (*3, 5*). Subjectively perceived sleep quality is relevant to health because it is an established factor that influences personal well-being (*29*). Collecting more sophisticated sleep measures using electroencephalography (EEG) would require considerable additional effort in this large study population, and such an unfamiliar measurement procedure could mask subtle effects on self-perceived sleep quality.

The participation rate for the full study (whole questionnaire data) was 37% and was therefore lower than we had expected and lower than in the study of Kühnlein *et al.* (*30*) and similar to that of Thomas *et al.* (*28*). In recent years, a decreasing response rate has been a commonly observed phenomenon in epidemiological research (*31*). In our study people might have declined because we asked them to give their informed consent to provide objective data about their mobile phone use from the mobile phone operator companies. People may have felt that it was an invasion of their privacy. The main concern in having a low participation rate is selection bias. We made considerable effort to evaluate potential bias from nonparticipation. To be able to assess the risk of selection bias, we performed nonresponder interviews, and data on age, gender and geocodes were available for all 4000 persons. We were concerned that people attributing their sleep disturbances to mobile phone base stations or to RF EMFs in general would be more motivated to participate in our survey (*32, 33*). If these people live closer to a mobile phone base station than the average population, this could result in a bias, because distance is one parameter of our exposure prediction model. Interestingly, we found indications of the opposite but yielding the same possible bias: Study participants generally were healthier than nonresponders, and the proportion of persons living close to a mobile phone base station (<50 m) was smaller for participants than nonparticipants. Thus our selection bias modeling yielded a selection bias factor of 1.33 for living within 50 m of a mobile phone base station. According to this selection bias modeling our observed exposure–response associations for fixed site transmitter may be biased upward. Conversely, our exposure–response associations for mobile and cordless phone use may be biased downward.

*Interpretation*

The prevalence of excessive daytime sleepiness in our study was similar to previous studies in which 32.4% reported suffering from excessive daytime sleepiness (*34*). Prevalence of sleep disturbances was in our study even lower (9.8%) than observed in a study of a Swiss working population (*20*), where 19% of a relatively young Swiss working population suffered from disorders of initiating and maintaining sleep.

**TABLE 4**
**Sensitivity Analysis to Evaluate the Possible Extent of Information Bias and Nocebo Effect: Association between Sleep Quality (excessive daytime sleepiness and self-reported sleep disturbances) and Subjective Exposure**

| | Excessive daytime sleepiness ($n$ = 1129) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Subjective exposure categories | | | | | | | |
| | equal[a] | | lower | | | higher | | |
| | No. of cases[b] | OR | No. of cases[b] | OR | 95% CI | No. of cases[b] | OR | 95% CI |
| Subjective exposure to all sources | | | | | | | | |
| Crude | 239 | 1.00 | 96 | 0.80 | (0.60–1.06) | 23 | 0.87 | (0.52–1.47) |
| Adjusted[c] | 239 | 1.00 | 96 | 0.78 | (0.56–1.09) | 23 | 0.84 | (0.41–1.71) |
| Subjective exposure to mobile phone base station | | | | | | | | |
| Crude | 243 | 1.00 | 85 | 0.71 | (0.53–0.95) | 30 | 0.98 | (0.62–1.59) |
| Adjusted[c] | 243 | 1.00 | 85 | 0.67 | (0.48–0.95) | 30 | 0.83 | (0.44–1.59) |
| | Excessive daytime sleepiness ($n$ = 1129) | | | | | | | |
| | > 50 m | | | | | ≤ 50 m | | |
| | No. of cases[b] | OR | | | | No. of cases[b] | OR | 95% CI |
| Distance to mobile phone base station (geo-coded) | | | | | | | | |
| Crude | 340 | 1.00 | - | - | - | 18 | 1.90 | (1.00–3.59) |
| Adjusted[c] | 340 | 1.00 | - | - | - | 18 | 2.06 | (0.96–4.41) |

[a] Reference group includes also "don't know" and missing values.
[b] Indicates number of people in the corresponding exposure group with an Epworth sleepiness score over 10 or a sleep quality score over 8, respectively.
[c] Adjusted for age, body mass index, sex, physical activity, alcohol consumption, smoking habits, stress perception, urban/suburban, marital status, educational level, noise perception, believe in health effects due to radiofrequency electromagnetic-field exposure.

We found no consistent evidence that RF EMF exposure is associated with subjective sleep quality. Our findings contradict early studies that used self-estimated distance to mobile phone base stations as exposure proxy (*9, 10*). This approach has been shown to be inappropriate for exposure estimation (*12, 14, 35*). Moreover, these early studies without objective exposure measures are likely to be affected by nocebo effects since we found some indication for such a bias in our study when using self-estimated exposure measures that were poorly correlated to true exposure levels. This was particularly pronounced with respect to self-estimated mobile phone base station radiation.

Our prediction models are developed and validated on the power flux density scale (mW/m$^2$). In our prediction model for everyday life exposure, we added up contributions from different sources on the power flux density scale, based on the assumption that effects are not dependent on frequency. It has also been speculated in other studies that effects in the low-dose range maybe dependent on frequency, and another study weighted the exposure contributions according to the ICNIRP reference level (*28*). However, for exposure from a fixed-site transmitter, where we were able to compare both scales, we found a very high correlation (Spearman = 0.96), and the results of the epidemiological analyses were similar. This suggests that choice of the exposure scale is not crucial unless the effect is very frequency specific.

Our findings are in line with more recent cross-sectional studies on subjective sleep quality that used spot measurements in the bedroom for exposure assessment (*15, 16*). This is probably an acceptable exposure proxy for environmental RF EMF exposure during the night, but it does not capture exposure during the day or exposure to close-to-body sources that one might be exposed to prior to sleep. However, such exposure may be relevant: Several studies indicated that exposure to a mobile phone prior to sleep affects EEG during the night (*7, 8, 36, 37*).

In addition to the cross-sectional studies on self-reported sleep quality and RF EMF exposure at home, two studies investigated sleep behavior at home using an experimental approach and recording polysomnographic sleep measures. In a German study of 394 individuals living within 500 m of a mobile phone base station, polysomnographic measures were recorded during five consecutive nights. A transportable mobile phone base station (GSM 900 and 1800) was installed and randomly turned on and off.[3] Leitgeb *et al.* (*38*) recruited 43 volunteers who reported to be EHS. Polysomnography was applied during 9 nights (3 control nights, 3 nights with sham shielding, and 3 nights with true shielding). In both studies, polysomnographic measures were not related to exposure.

[3] H. Danker-Hopfe, H. Dorn, C. Sauter and M. Schubert, Untersuchung der Schlafqualität bei Anwohnern einer Basisstation. Experimentelle Studie zur Objektivierung möglicher psychologischer und physiologischer Effekte unter häuslichen Bedingungen. Final report. Deutsches Mobilfunkforschungsprogramm, 2009.

**TABLE 4**
**Extended**

| Self-reported sleep disturbances ($n$ = 1163) | | | | | | | |
|---|---|---|---|---|---|---|---|
| Subjective exposure categories | | | | | | | |
| equal[a] | | lower | | | higher | | |
| No. of cases[b] | OR | No. of cases[b] | OR | 95% CI | No. of cases[b] | OR | 95% CI |
| 116 | 1.00 | 49 | 0.92 | (0.64–1.32) | 15 | 1.23 | (0.67–2.27) |
| 116 | 1.00 | 49 | 1.05 | (0.68–1.64) | 15 | 1.47 | (0.62–3.49) |
| 109 | 1.00 | 47 | 1.08 | (0.74–1.56) | 24 | 1.99 | (1.20–3.30) |
| 109 | 1.00 | 47 | 1.16 | (0.74–1.82) | 24 | 1.61 | (0.76–3.43) |
| Self-reported sleep disturbances ($n$ = 1163) | | | | | | | |
| > 50 m | | | | | ≤ 50 m | | |
| No. of cases[b] | OR | | | | No. of cases[b] | OR | 95% CI |
| 171 | 1.00 | - | - | - | 9 | 1.53 | (0.72–3.25) |
| 171 | 1.00 | - | - | - | 9 | 1.13 | (0.41–3.04) |

We evaluated various exposure proxies. Except in a subgroup analysis with non-sensitive individuals for excessive daytime sleepiness and cordless phone use, no statistically significant effects were found. Given the numerous tests performed, one statistically significant result can be expected by chance. Similarly, some of the observed exposure–response tendencies such as the decreased occurrence of sleep disturbances for the moderate user of cordless phones are probably due to chance or may be affected by selection bias. If there were a true exposure–response association in our large study population, we would have expected to see a consistent pattern in terms of outcome (i.e., similar effects for sleep quality or daytime sleepiness) or in terms of exposure sources (i.e., similar effects for close-to-body sources or for environmental sources). Nevertheless, the cross-sectional design is a limitation, particularly if one has the hypothesis that people avoid exposure if they are suffering from sleep disturbances. In our study we found no evidence for such a behavior, nor have recent reviews suggested that the ability to perceive RF EMF exposure actually exists (*14, 39*).

Overall, we found no indication that RF EMF exposure in our daily life impairs subjective sleep quality. In contrast to previous studies on that topic, we considered all relevant RF EMF sources of the everyday environment in our exposure assessment through consideration of various proxies that are relevant in everyday life.

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# **Article 4:** Exposure to radiofrequency electromagnetic fields and sleep quality: a prospective cohort study

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# Exposure to Radiofrequency Electromagnetic Fields and Sleep Quality: A Prospective Cohort Study

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## Abstract

***Background:*** There is persistent public concern about sleep disturbances due to radiofrequency electromagnetic field (RF-EMF) exposure. The aim of this prospective cohort study was to investigate whether sleep quality is affected by mobile phone use or by other RF-EMF sources in the everyday environment.

***Methods:*** We conducted a prospective cohort study with 955 study participants aged between 30 and 60 years. Sleep quality and daytime sleepiness was assessed by means of standardized questionnaires in May 2008 (baseline) and May 2009 (follow-up). We also asked about mobile and cordless phone use and asked study participants for consent to obtain their mobile phone connection data from the mobile phone operators. Exposure to environmental RF-EMF was computed for each study participant using a previously developed and validated prediction model. In a nested sample of 119 study participants, RF-EMF exposure was measured in the bedroom and data on sleep behavior was collected by means of actigraphy during two weeks. Data were analyzed using multivariable regression models adjusted for relevant confounders.

***Results:*** In the longitudinal analyses neither operator-recorded nor self-reported mobile phone use was associated with sleep disturbances or daytime sleepiness. Also, exposure to environmental RF-EMF did not affect self-reported sleep quality. The results from the longitudinal analyses were confirmed in the nested sleep study with objectively recorded exposure and measured sleep behavior data.

***Conclusions:*** We did not find evidence for adverse effects on sleep quality from RF-EMF exposure in our everyday environment.

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## Introduction

In the last two decades, emerging wireless technologies like mobile or cordless phones have led to increasing exposure to radiofrequency electromagnetic fields (RF-EMF) in everyday life [1,2]. As a consequence, public concern about possible health effects due to RF-EMF exposure arose and various representative population surveys in Europe reported that sleep disturbances were the most common health complaints attributed to RF-EMF exposure [3–5].

Several randomized, double blind studies addressed the question whether short-term RF-EMF exposure affects sleep measures such as brain activity recorded by means of electroencephalography (EEG). Most of the studies were conducted in a laboratory setting applying well controlled exposure conditions mimicking a mobile phone handset exposure during 30 to 45 minutes [6–11]. Overall, these laboratory studies demonstrated fairly consistently that exposure prior to sleep increased the power in the spindle frequency range during sleep stage 2 of the non-REM sleep in the first few hours of sleep. It is unclear whether these changes in sleep EEG indicate adverse health effects or detrimental sleep quality. Interestingly, two studies that observed effects of mobile phone handset exposure on the EEG and that also investigated subjectively rated sleep quality did not find alterations in subjectively rated sleep quality [8,10]. However, the statistical power of these studies to detect such effects on sleep quality is low because of the small sample size. Moreover, subtle effects on sleep quality may not be observable in an unfamiliar environment of a sleep laboratory with electrodes attached to the head. Epidemiological studies allow for investigating larger populations and are also suitable to address effects of prolonged exposure of several months or even years. So far, no epidemiological study has explored the effect of mobile phone use on sleep using objectively recorded data on mobile phone use provided by network operators. The few studies dealing with self-reported mobile phone use [12] are not reliable as self-reported exposure data in combination with self-reported outcomes are prone to bias [13].

Mobile and cordless phones produce a relatively high exposure to the head but not to the rest of the body as EMF is rapidly decreasing with distance [2]. As a consequence cumulative RF-EMF exposure of a moderate or heavy wireless phone user is dominated by these close to body sources [1]. On the other hand, environmental RF-EMF sources such as mobile phone base stations, broadcast transmitter or W-LAN access points, produce a continuous but lower and more homogenous exposure to the whole body. Interestingly the public is more concerned about health effects from these environmental RF-EMF sources [5,14]. In response to these public complaints, a few epidemiological studies on sleep quality addressed exposure from mobile phone bases stations [15–17]. These studies did not indicate an exposure-response association; however, their reliability is limited due to their cross-sectional design.

Thus, there is an urgent need for a prospective cohort study on sleep quality addressing all aspects of RF-EMF exposure in our everyday life, which includes exposure to environmental far-fields (e.g. mobile phone base stations) and exposure to sources close to the body localized to the head (mobile and cordless phone use). The aim of this study was to investigate a possible association between different objective RF-EMF exposure surrogates and self-reported sleep quality in a large sample (longitudinal study) and to check the consistency of the results in a subsample with measured RF-EMF exposure and measured sleep behavior data (nested sleep study). Main characteristics of these two study components are presented in Table 1.

## Materials and Methods

### Ethics statement

Ethical approval for this study was received from the Ethical Commission of Basel on March 19th, 2007 (EK: 38/07). Written informed consent was obtained from the participants of the nested sleep study and of the participants of the longitudinal study for providing the mobile phone operator data.

### Longitudinal study

For the present study, we invited 3763 residents from the Basel area (Switzerland) randomly selected from communal population registries. Eligible participants were between 30 and 60 years old, Swiss residents or people who lived in Switzerland for at least five years. A baseline survey was conducted in May 2008 and the follow-up in May 2009. Information was collected on sleep quality, possible confounders and relevant exposure predictors including use of mobile and cordless phones. Exclusion criteria for the analyses of sleep data presented in this paper were regular usage of sleeping pills and night shift working either at the baseline or follow-up survey.

In the written questionnaire of the baseline and the follow-up questionnaire, we used seven items of the Epworth Sleepiness Scale [18] ranging from 0 (no daytime sleepiness) to 21 (excessive daytime sleepiness) to assess excessive daytime sleepiness. Due to a technical problem in the production of the questionnaire, the eighth question from the Epworth Sleepiness Score was accidentally skipped ("Lying down to rest in the afternoon when circumstances permit"). Sleep disturbances were determined by means of four standardized questions from the Swiss Health Survey 2007 [19]. The four questions asked about the frequency of

**Table 1.** Overview on the two study components.

| Study characteristics | Longitudinal study | Nested sleep study |
|---|---|---|
| Number of participants | 955[a)] | 119[b)] |
| Outcomes | Written questionnaire: | Actigraphy: |
| | - daytime sleepiness | - sleep duration |
| | - sleep disturbances | - sleep efficiency |
| | | Sleep diary: |
| | | - restfulness of sleep |
| | | - wellbeing in the morning |
| Exposure measures | Written questionnaire: | Personal measurements: |
| | - mobile phone use | - everyday life exposure to all sources (during one typical working day) |
| | - cordless phone use | - night-time exposure to all sources in the bedroom |
| | Operator recorded data: | - fixed site transmitter exposure in the bedroom |
| | - mobile phone use | |
| | Modelling: | |
| | - everyday life exposure to all sources | |
| | - night-time exposure to all sources in the bedroom | |
| | - fixed site transmitter exposure in the bedroom | |
| Type of data analysis | Longitudinal: | Cross-sectional: |
| | - cohort analysis | - random effect regression models with a 1-day lag autocorrelation term |
| | - change analysis | |

a)After exclusion of nightshift workers (n = 89) and users of sleeping drugs (n = 81).
b)1 person was excluded because of sleeping drug consumption during all 14 nights.
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difficulty in falling asleep, fitful sleep, waking phases during night, and waking too early in the morning using a four-point Likert scale with categories "never", "rare", "sometimes" and "most of the time". All items were added up and a linear score ranging from 0 (no sleep disturbances) to 12 (heavy sleep disturbances) was built.

Due to the unknown mechanism of radiofrequency electromagnetic radiation on biological organisms, we used six different exposure surrogates to assess far field exposure and exposure from sources operating close to the body. With respect to local exposure to the head (close to body exposure), we asked participants in the written questionnaire about their average mobile and cordless phone use per week during the past six months. Informed consent was also sought from participants to obtain their mobile phone connection data for the previous six months of each survey from the three Swiss mobile phone network operators (operator data).

For far field exposure, we used a three-dimensional geospatial propagation model in which average RF-EMF from fixed site transmitters (mobile phone base stations and broadcast transmitters) was modeled for the apartment of each study participant [20]. The model was validated in an independent dataset. Additionally, to predict total personal far-field exposure to all relevant environmental RF-EMF sources, we developed and validated a prediction model [21]. This model is based on the geospatial propagation model and includes additional exposure relevant factors such as housing characteristics (type of house wall and window frame) and behavioral factors (e.g. ownership of a cordless phone or wireless LAN). A separate model was developed to estimate total environmental RF-EMF exposure during night.

## Nested sleep study

From the responders of the baseline cohort survey, 120 participants were selected for a nested sleep study. We did not recruit persons with children less than two years, people who had experienced a long distance flight within the last three weeks, people with severe illnesses, people who regularly consumed sleeping pills and shift workers. We used our exposure prediction model to oversample highly exposed persons to maximize the exposure range in the nested sleep study.

In the participants of the nested sleep study, sleep behavior was measured by means of a wrist actigraphic device (AW7, Cambridge Neurotechnology) with an epoch length of 15 seconds during two weeks. Participants were asked to wear this device on the non-dominant wrist during two weeks and were advised to press an event marker when trying to fall asleep or getting up. They also received a sleep diary, which they had to fill in every morning and every evening. This diary was based on the sleep diary suggested by the German Society of Sleep Medicine (http://www.charite.de/dgsm/dgsm/fachinformationen_frageboegen_schlaftagebuecher.php?language=german) collecting information on waking phases during the night, alcohol and caffeine consumption prior to sleep, and physical activity during the day. The sleep diary also provided backup data for bedtime and getting up time in case participants forgot to press the event marker of the actimeter. In the morning participants rated the restfulness of the sleep using a scale from 1 (very restless sleep) to 5 (very restful sleep) as well as their well-being using a scale from 1 (depressed) to 6 (easygoing).

Actigraphic data were analyzed using the software provided by the manufacturer. A study assistant checked the night data for artifacts and the diary data were systematically used for data quality control. Nights in which participants forgot to wear the actigraphic device were replaced with the data from the sleep diary. We excluded from the data analysis nights during which a switching from daylight saving time to regular time and vice versa took place, nights when participants slept at another place or nights with sleeping pill consumption. Two sleep parameters were

**Table 2.** Definition and distributions of the sleep quality parameters.

| | Parameter | Definition | Data sources | Min. | Median | $90^{th}$ perc. | Max. |
|---|---|---|---|---|---|---|---|
| **Longitudinal study (n = 955)** | Epworth sleepiness scale (ESS) | Excessive daytime sleepiness | Questionnaire | 0 | Baseline: 5 | 10 | 19 |
| | | | | | Follow-up: 4 | 9 | 21 |
| | Sleep disturbance score | Difficulties with falling asleep, fitful sleep, waking phases during night and awaking too early in the morning | Questionnaire | 0 | Baseline: 5 | 9 | 12 |
| | | | | | Follow-up: 5 | 8 | 12 |
| **Sleep study (n = 119)** | Total sleep duration [h] | Time from sleep onset to sleep end excluding waking phases | Actigraphy | 4.8 | 7.1 | 8.0 | 9.7 |
| | Sleep efficiency [%] | Percentage of time in bed with the intention to sleep that a person sleeps | Actigraphy | 79.0 | 91.2 | 95.1 | 96.9 |
| | Restfulness of sleep | How restful was your sleep? 1 "very restless sleep" to 5 "very restful sleep" | Sleep diary | 2.8 | 4 | 4.6 | 5 |
| | Well-being in the morning | How do you feel now? 1 "depressed" to 6 "easygoing" | Sleep diary | 1.5 | 4.5 | 5.8 | 6 |

For the sleep study, all estimates are given for the level of the individual (i.e. average over two weeks).
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extracted from the actigraphic measurements: total sleep duration and sleep efficiency. Definitions of these parameters are given in Table 2.

Exposure to all relevant sources of radiofrequency electromagnetic fields was measured with the EME SPY120 (Satimo, Courtaboeuf, France). Exposure measures were taken every 90 seconds during the first week of the measurement period (two weeks). The exposure meter device (exposimeter) was placed in the sleeping room near the bed and the head of the participants. During one typical working day participants were requested to wear the exposimeter to estimate their daytime exposure. Mean exposure values were calculated for measurements in the sleeping room during the night, for fixed site transmitter measurements in the sleeping room and for measurements during the day on which the exposimeter was carried around. Mean values were calculated using regression on order statistics, which allows for nondetects [22]. Missing exposure measurements occurred due to technical problems in 6 participants and 29 participants did not have daytime measurements. Those missing values were replaced with data from the prediction model [21], night-time measurements were replaced with the prediction model for night exposure and exposure to fixed side transmitters was replaced by values of the geospatial propagation model [20].

## Statistical analyses

In the longitudinal study, the association between exposure and outcome was calculated by means of linear regression models. We conducted two different analyses: I) A cohort analysis, where we assessed the association between exposure at baseline and the change in self-reported sleep quality within one year. Three exposure categories were defined a priori for each exposure metric: $<50^{th}$ percentile, $50^{th}$ to $90^{th}$ percentile, $>90^{th}$ percentile. II) A change analysis, where we examined whether the change in exposure between baseline and follow-up resulted in a change in self-reported sleep quality. For the change analysis we compared the participants with the 20% largest exposure increase and decrease between baseline and follow-up survey with all other participants who experienced a smaller or no change of exposure between baseline and follow-up survey (reference group). All models were adjusted for age, sex, body mass index, stress level, physical activity per week, smoking status, alcohol consumption, education level, marital status, degree of urbanity, belief in health effects due to RF-EMF exposure, noise annoyance and for moving house between the two surveys. About 20% of the participants in each survey reported to be electro-hypersensitive (EHS) or reported that they thought that they developed detrimental health symptoms due to electromagnetic pollution in everyday life [23]. All models were thus tested for interaction between EHS status and the exposure measures in order to evaluate whether EHS individuals are differently affected by RF-EMF exposure.

In the nested sleep study, we used a random intercept mixed regression model with an autocorrelation term of one-day lag to analyze the association between sleep measures and RF-EMF exposure. All models were adjusted for sex, age, smoking status, body mass index, weekday, percent fulltime equivalent, educational level, presence of a bed partner, weekday and the diary-based variables bedtime, alcohol intake within 4 hours before going to bed, physical activity during the day, and sleeping during the day (more information on the confounders is given in the footnote in Table 3). We built three exposure categories: <median (reference group), $50^{th}$–$90^{th}$ percentile, $>90^{th}$ percentile.

All statistical analyses were carried out using STATA 10.1 (StataCorp, College Station, TX, USA).

# Results

## Study population

In total, 1375 participants filled in the baseline questionnaire in 2008 and 1125 subjects filled in the follow-up questionnaire one year later (response rate 82%). 170 participants were excluded from the longitudinal analyses due to night shift working (89 participants) and consumption of sleeping pills (81 participants). The analyses of our longitudinal study were therefore performed with 955 subjects. Detailed information on the characteristics of the study participants are described in Table 4. Average age of the participants was 47 years. Generally, characteristics of the study participants in the baseline and follow-up survey were comparable [24]. Health status was generally good in all participants.

In the nested sleep study, age and gender distribution were comparable with participants of the longitudinal study (Table 4). Twenty-two percent of the participants of the nested sleep study lived alone, 48% with a partner and 30% with children. Sleeping data for 1680 nights were collected from 120 participants. One person was excluded from all analyses due to sleeping drug consumption during all 14 nights. At the time of recruitment, this person did not state that he/she regularly took sleeping pills. Additionally, a total number of 115 nights were excluded from data analyses because participants did not sleep in their own house (77 nights), and/or due to clock change (16 nights), and/or due to sleeping pill consumption (10 nights) and/or because both actigraphic measurements and sleep diary data were missing (18 nights).

## Exposure to RF-EMF

Table 5 shows the ranges of the RF-EMF levels in all exposure categories of the various exposure metrics for the longitudinal study at baseline (cohort analysis) and the changes between baseline and follow-up survey (change analysis). At baseline self reported arithmetic mean mobile phone use was 61.6 minutes per week. Arithmetic mean cordless phone use was 73.8 minutes per week. For the subset of 389 study participants who consented to provide operator recorded connection data, recorded arithmetic mean duration of mobile phone use was 26.4 minutes and self-reported mobile phone use was 47.7 minutes per week. Time-weighted arithmetic mean RF-EMF exposure at baseline was 0.12 $mW/m^2$ for everyday life exposure, 0.02 $mW/m^2$ for fixed site transmitters and 0.01 $mW/m^2$ during night.

Measured exposure levels of the nested sleep study are presented in Table 3. Measured arithmetic average exposure in the sleeping room during the night was 0.11 $mW/m^2$. Average exposure to fixed site transmitters in the sleeping room was 0.08 $mW/m^2$. Arithmetic mean measured daytime exposure during a typical working day was 0.35 $mW/m^2$.

## Self reported sleep quality (longitudinal study)

Median daytime sleepiness and sleep disturbances scores per individual at baseline and follow-up are presented in Table 2. The results of the longitudinal analyses on daytime sleepiness are presented in Figure 1 and the results on self-reported sleep disturbances in Figure 2. Overall, six out of 48 effect estimates for the six exposure metrics reached statistical significance. These significant effects concerned different exposure surrogates and outcomes. There was neither a consistent increase in self-reported daytime sleepiness or sleep disturbances if exposure at baseline was high, nor was a change in RF-EMF exposure consistently accompanied by a corresponding change in daytime sleepiness. Generally, interaction testing did not yield a difference in

**Table 3.** Change of sleep duration (in hours) and sleep efficiency (in %) (95%-confidence interval (CI)) for various exposure measures from the nested sleep study.

| | | Linear multilevel model[a)] | | | |
|---|---|---|---|---|---|
| | Exposure range [mW/m$^2$] | n (individuals)[b)] | n (nights) | Coeff. | (95%-CI) |
| **Total sleep duration in h** | | | | | |
| **Total everyday life exposure** | | | | | |
| <median | 0.00 to 0.11 | 60 | 777 | 0.00 | |
| 50.–90. percentile | 0.11 to 0.42 | 48 | 616 | 0.07 | (−0.18;0.32) |
| >90. percentile | 0.45 to 16.69 | 11 | 158 | 0.19 | (−0.21;0.60) |
| **Night-time exposure** | | | | | |
| <median | 0.00 to 0.03 | 60 | 763 | 0.00 | |
| 50.–90. percentile | 0.03 to 0.12 | 48 | 624 | 0.16 | (−0.09;0.41) |
| >90. percentile | 0.12 to 2.18 | 11 | 164 | 0.16 | (−0.24;0.56) |
| **Fixed site transmitter** | | | | | |
| <median | 0.00 to 0.01 | 60 | 778 | 0.00 | |
| 50.–90. percentile | 0.02 to 0.06 | 48 | 622 | 0.07 | (−0.17;0.32) |
| >90. percentile | 0.08 to 1.39 | 11 | 151 | 0.00 | (−0.43;0.43) |
| **Sleep efficiency in percent** | | | | | |
| **Total everyday life exposure** | | | | | |
| <median | 0.00 to 0.11 | 60 | 777 | 0.00 | |
| 50.–90. percentile | 0.11 to 0.42 | 48 | 616 | 1.21 | (−0.02;2.44) |
| >90. percentile | 0.45 to 16.69 | 11 | 158 | 0.43 | (−1.54;2.41) |
| **Night-time exposure** | | | | | |
| <median | 0.00 to 0.03 | 60 | 763 | 0.00 | |
| 50.–90. percentile | 0.03 to 0.12 | 48 | 624 | 0.80 | (−0.41;2.01) |
| >90. percentile | 0.12 to 2.18 | 11 | 164 | −0.67 | (−2.60;1.27) |
| **Fixed site transmitter** | | | | | |
| <median | 0.00 to 0.01 | 60 | 778 | 0.00 | |
| 50.–90. percentile | 0.02 to 0.08 | 48 | 622 | 0.80 | (−0.40;1.99) |
| >90. percentile | 0.10 to 1.40 | 11 | 151 | −1.04 | (−3.11;1.02) |

[a)]adjusted for: age, percent fulltime equivalent, bedtime (derived from diary) (all linear), sex, body mass index (<25, ≥25), smoking status, weekday (weekend vs. workday), presence of a bed partner, alcohol intake within 4 hours before going to bed (diary), physical activity during the day (diary), sleeping during the day (diary) (all binary), and educational level (3 categories).
[b)]The division into the exposure categories was done on the individual level.
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development of sleep disturbances and daytime sleepiness of EHS and non-EHS individuals (data not shown).

## Sleep behavior (nested sleep study)

Measured arithmetic mean sleep duration per individual was 6.9 hours (h) during weekdays (range: 4.9 h to 9.4 h) and 7.8 h during weekends (range: 4.5 h to 11.9 h) (Table 2). Sleep efficiency was on average 91.0% (range: 79.0% to 96.9%) and did not differ statistically significantly between weekdays and weekends. Mean sleep duration (7.1 h vs. 7.2) and mean sleep efficiency (91.0% vs. 91.9%) were similar for actigraphic measurements and self-reports. In Table 3, results of the regression analyses for sleep duration and sleep efficiency are presented for the three measured exposure surrogates. Neither typical everyday exposure to all RF-EMF sources, nor night-time exposure, nor exposure from fixed site transmitters was significantly associated with sleep duration or sleep efficiency. Additionally, we investigated whether RF-EMF exposure was related to self-reported restfulness of sleep as rated each morning in the sleep diary. For all three exposure measures, restfulness of sleep in the participants in the top exposure decile was not significantly altered compared to the reference category: change in score for total everyday exposure was 0.14 units (95% confidence interval: −0.13 to 0.41), for night-time exposure 0.06 units (95% CI: −0.20 to 0.32) and for exposure to fixed site transmitters −0.04 units (95% CI: −0.33 to 0.25). Similarly, well-being in the morning was not related to any of the RF-EMF exposure surrogates (data not shown).

## Discussion

This study did not find indications for an association between typical levels of RF-EMF exposure in an everyday environment and self-reported sleep disturbances or excessive daytime sleepiness considering an exposure period of one year. These results were confirmed in a subsample of 119 study participants with data on sleep behavior measured with actigraphic devices and measured RF-EMF exposure.

**Table 4.** Characteristics of the study participants of the longitudinal study at follow-up (baseline data are presented in Mohler et al. 2010 [24]) and of the participants of the nested sleep study.

| | *Longitudinal study (n = 955)* | % | *Nested study (n = 119)* | % |
|---|---|---|---|---|
| Age (years) | | | | |
| 30–40 | 224 | 24 | *26* | *22* |
| 41–50 | 329 | 34 | *36* | *30* |
| 51–60 | 402 | 42 | *57* | *48* |
| Sex | | | | |
| Female | 578 | 61 | *73* | *61* |
| Male | 377 | 39 | *46* | *39* |
| Health status[a)] | | | | |
| Very good | 323 | 34 | *45* | *38* |
| Good | 530 | 56 | *64* | *54* |
| Half-half | 83 | 9 | *10* | *8* |
| Bad | 8 | 1 | *0* | *0* |
| Very bad | 1 | <1 | *0* | *0* |
| Educational level[a)] | | | | |
| None | 51 | 5 | *2* | *2* |
| Apprenticeship | 456 | 48 | *60* | *50* |
| Higher education/University | 448 | 47 | *57* | *48* |
| Self-reported electromagnetic hypersensitivity[a,b)] | | | | |
| Yes | 195 | 20 | *23* | *19* |
| No | 760 | 80 | *96* | *81* |
| Owning a mobile phone[a)] | | | | |
| Yes | 909 | 95 | *107* | *90* |
| No | 41 | 4 | *12* | *10* |
| Owning a cordless phone[a)] | | | | |
| Yes | 800 | 84 | *87* | *73* |
| No | 150 | 16 | *32* | *27* |
| Owning wireless LAN[a)] | | | | |
| Yes | 390 | 41 | *57* | *48* |
| No | 558 | 59 | *62* | *52* |

[a)]Data may not sum up to 100% due to missing data.
[b)]Answering yes to either "Are you electro hypersensitive?" or "Do you think that you develop detrimental health symptoms due to electromagnetic pollution in everyday life?"
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## Strength and limitations

To the best of our knowledge this is the first longitudinal study investigating the association between RF-EMF exposure and self-reported sleep quality in a large population sample using objectively recorded exposure data and data on sleep behavior measured with actigraphic devices. The cohort design allows for more robust conclusions, particularly because participation rate in the follow-up survey was rather high (82%). Therefore, in the present cohort and change analyses of the longitudinal study selection bias is expected to be of minor concern.

We applied a comprehensive exposure assessment method. All RF-EMF sources relevant in our everyday environment are included in the model and also personal exposure relevant behaviors are considered. The prediction models of the longitudinal study are based on extensive measurements with personal dosimetric devices. For the development of these prediction models we used weekly measurements of 166 persons and conducted a validation study by repeating the exposure measurements in 31 study participants 21 weeks later on average. In this validation study agreement between personal measurements and the prediction model for everyday exposure was found to be good (Spearman rank correlation: 0.75 (95%-CI 0.53–0.87), sensitivity: 0.67 and specificity 0.96) [21]. To consider the impact of close to body sources, we included self-reported mobile and cordless phone use as well as objective information on mobile phone use from participants who gave their informed consent. Three Swiss mobile phone network operators provided this information. Additionally, we were able to verify our results of the longitudinal analyses with measured data on sleep behavior and environmental RF-EMF exposure in the nested sleep study.

The subjective sleep parameters in the longitudinal study might be considered a weakness of this study. However, we used standardized questions to assess daytime sleepiness and sleep disturbances. Subjectively perceived sleep quality is an established factor influencing personal well-being and is thus health relevant [25]. Alternatively, polysomnographic records could have been

**Table 5.** Exposure ranges of the longitudinal study for all study participants (n = 955): ranges in power flux densities to different exposure sources for all included study participants at follow-up survey and the change in exposure levels between baseline and follow-up.

| | Exposure at baseline | | Change (between baseline and follow-up) | |
|---|---|---|---|---|
| Close to body exposure | | | | |
| **Mobile phone use [h/week]** | <Median | 0.00 to 0.23 | Decrease | −11.67 to −0.15 |
| | 50th–90th percentile | 0.23 to 3.50 | No relevant change | −0.13 to 0.15 |
| | >90th percentile | 3.50 to 17.5 | Increase | 0.15 to 17.50 |
| **Operator data[a] [h/week]** | <Median | 0.00 to 0.15 | Decrease | −2.85 to −0.18 |
| | 50th–90th percentile | 0.16 to 1.30 | No relevant change | −0.17 to 0.04 |
| | >90th percentile | 1.33 to 8.61 | Increase | 0.04 to 1.49 |
| **Cordless phone use [h/week]** | <Median | 0.00 to 0.35 | Decrease | −9.27 to −0.58 |
| | 50th–90th percentile | 0.93 to 4.67 | No relevant change | −0.35 to 0.58 |
| | >90th percentile | 9.33 to 9.33[b] | Increase | 0.87 to 9.33 |
| Far field exposure | | | | |
| **Total exposure [mW/m$^2$]** | <Median | 0.00 to 0.12 | Decrease | −0.14 to −0.02 |
| | 50th–90th percentile | 0.12 to 0.17 | No relevant change | −0.02 to 0.03 |
| | >90th percentile | 0.17 to 0.41 | Increase | 0.03 to 0.18 |
| **Exposure during night [mW/m$^2$]** | <Median | 0.00 to 0.00 | Decrease | −0.23 to −0.00 |
| | 50th–90th percentile | 0.00 to 0.04 | No relevant change | −0.00 to 0.00 |
| | >90th percentile | 0.05 to 0.40 | Increase | 0.00 to 0.23 |
| **Residential exposure through fixed site transmitters [mW/m$^2$]** | <Median | 0.00 to 0.01 | Decrease | −0.16 to −0.00 |
| | 50th–90th percentile | 0.01 to 0.05 | No relevant change | −0.00 to 0.00 |
| | >90th percentile | 0.05 to 1.43 | Increase | 0.00 to 0.62 |

For the change analysis we compared the participants with the 20% largest exposure increase and decrease between baseline and follow-up survey with all other participants, who experienced a smaller or no change of exposure between baseline and follow-up survey (no relevant change).
a) n = 389 at baseline (cohort analyses) and n = 245 at follow-up (change analyses).
b) equal values due to the use of categories in the questionnaire.
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used to obtain sleep measures. However, this method may have affected sleep quality of the participants and we were also concerned that such a demanding task for study participants could have created considerable selection bias by attracting mainly persons who are concerned about EMF exposures. As a consequence we used actigraphy, a more convenient tool for study participants, to collect measured data on sleep behavior in the nested sleep study. With these data we could confirm the results of the longitudinal analysis.

With respect to self-reported outcome measures, information bias may be of concern if study participants are aware of their exposure status. For instance, individuals who consider themselves as exposed to mobile phone base station radiation may claim to suffer more often from sleep disturbances. There is some evidence from laboratory trials that more symptoms are reported in open provocations where participants were aware about the exposure status than in subsequent double blind provocations [26–28]. However, we could demonstrate in our study that self-estimated RF-EMF exposure to far-field environmental sources is not correlated to objective exposure measured with an exposimeter [29]. Thus, our self-reported outcomes are most likely not affected by information bias.

## Interpretation

We did not find an association between self-reported sleep quality and prolonged exposure to RF-EMF. Our findings are in line with results of cross-sectional surveys about RF-EMF exposure and self-reported sleep quality, which used spot measurements to assess exposure [15,16], 24 h personal measurements [17], or applied a double blind field experiment with mobile phone base stations [17,30]. Spot measurements have been shown to be an appropriate exposure proxy [29], but, in contrast to our study, not all relevant sources and only exposure at home is measured. In particular, exposure from mobile phone handsets is not considered. This is a relevant exposure source for a sleep study since it is the most relevant exposure source for the head and various randomized trials found increased power in the spindle frequency range if study subjects were exposed to mobile phones prior to sleep [8–10]. This is the first epidemiological study on sleep quality using operator recorded mobile phone use and not only self-estimated exposure data.

We conducted a large number of analyses because in the absence of a known biological mechanism in the low dose range, it was unclear which aspect of exposure might be relevant for sleep disturbances, if any at all. We simultaneously took into account exposure from sources close to the body, producing high, localized and short-term exposures, as well as sources further away, which typically cause lower, more homogenous long-term exposures. Since mobile phone base stations are the EMF source people in Switzerland are most concerned about [5], we wanted to consider the effect of exposure to fixed site transmitters separately. We did not apply a formal multiple endpoint correction (e.g. Bonferroni correction). Instead we checked the consistency and biological plausibility of similar analyses.

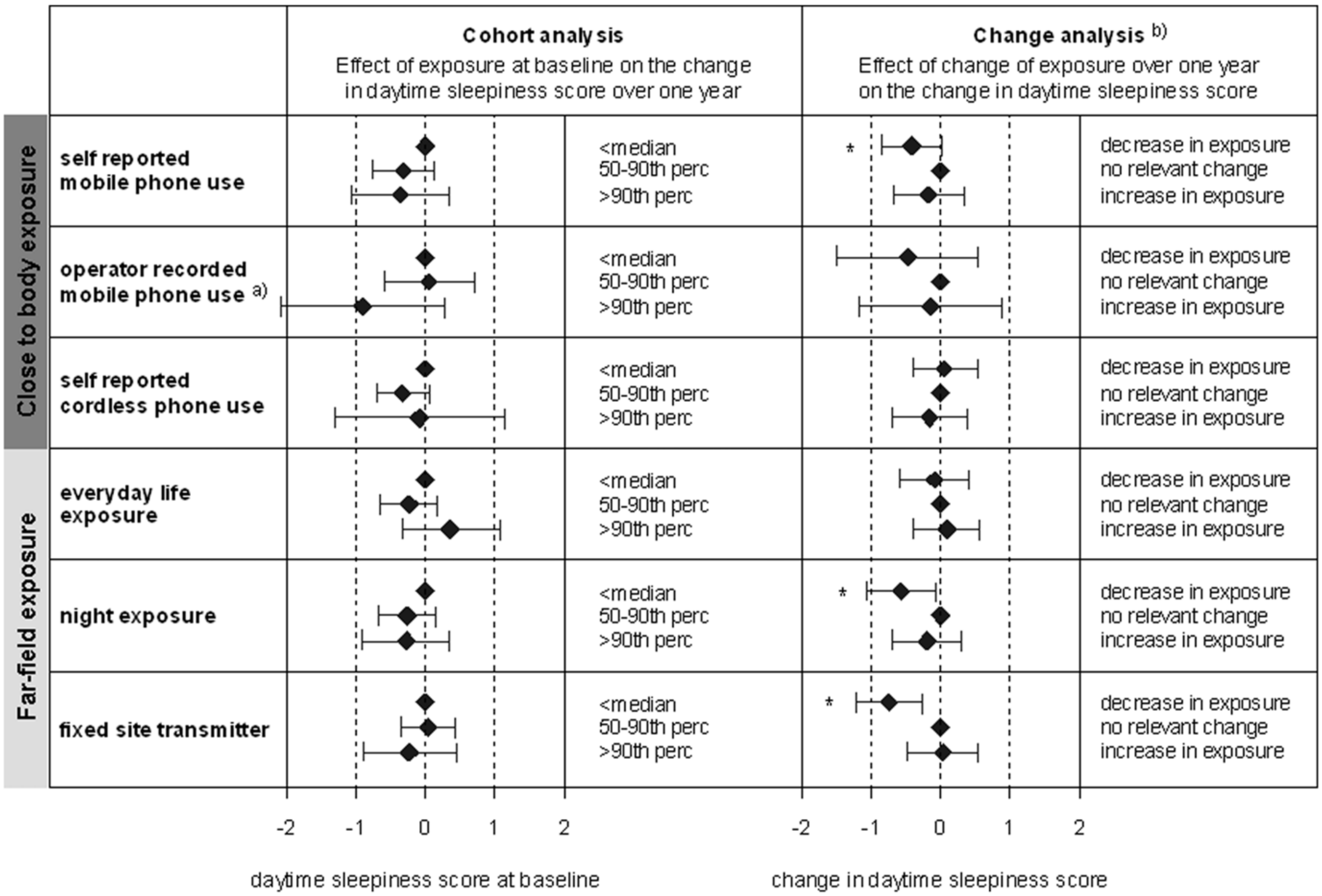


**Figure 1. Results of the longitudinal analysis on daytime sleepiness score: Diamonds refer to the change in sleep score and the horizontal lines mark the 95% confidence intervals.** An increase in score refers to an increase in daytime sleepiness. * indicates statistical significance. All models are adjusted for age, body mass index, stress level, physical activity, noise annoyance (all linear), sex, alcohol consumption, belief in health effects due to RF-EMF exposure, smoking status, degree of urbanity, moving house between the two surveys (all binary), educational level, marital status (categorical). [a] for a subsample of 363 (225) subjects who consented that we receive data from the operator at baseline (follow-up). [b] In the change analysis a decrease and increase in exposure refers to the participants with the 20% largest exposure decrease and increase between baseline and follow-up survey. No relevant change includes all other participants, who experienced a smaller or no change of exposure (reference group).
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Given the absence of an observed association, non-differential exposure misclassification may be of concern. For such ubiquitously distributed exposure sources, some exposure misclassification is unavoidable although we have put considerable effort in validating our methods. Non-differential exposure misclassification is expected to shift the regression coefficients towards zero if there is a true association. Nevertheless, assuming there is a true association, we would expect to see a non-significant exposure-response pattern consistently pointing towards an association. However, this was not observed in our study neither in the direction of a harmful nor in the direction of a beneficial effect. For interpretation of this and similar studies on symptoms, a "healthy communicator effect" may be relevant. Healthy communicator effect refers to the possibility that healthy people may use more often wireless communication devices and thus may be more exposed than ill people. It can thus be considered an analogy to the well known healthy worker effect.

In our study we observed relatively low far-field exposure levels. The levels were far below current standard limits [31] but representative for the RF-EMF exposure situation in the years 2007–2009 in an urban and suburban environment. Also the changes in exposure levels between baseline and follow-up survey were relatively small. Therefore, we are only able to draw conclusions about consequences of small exposure levels and changes, respectively.

We found no evidence that individuals who reported to react sensitively to EMF (electromagnetic hypersensitivity) were more vulnerable to RF-EMF exposure than the rest of the population. This is in line with reported randomized double blind provocation studies addressing short term effects [13,32]. However, observational research in EHS individuals is limited if one assumes that EHS individuals tend to avoid EMF exposure. If such an intentionally achieved exposure reduction results in a better health status, it could either be mediated by a biophysical mechanism or by a pure nocebo mechanism. In our study, however, we did not observe such changes.

Our longitudinal study captured a latency period of one year. It is not clear whether such a period is sufficient for sleep effects to manifest. Thus, we cannot completely rule out that our study has missed sleep effects that occur after prolonged exposure duration. However, most individuals who reported sleep disturbances in relation to mobile phone base station exposure claimed that such symptoms have occurred within a few days or weeks after a new

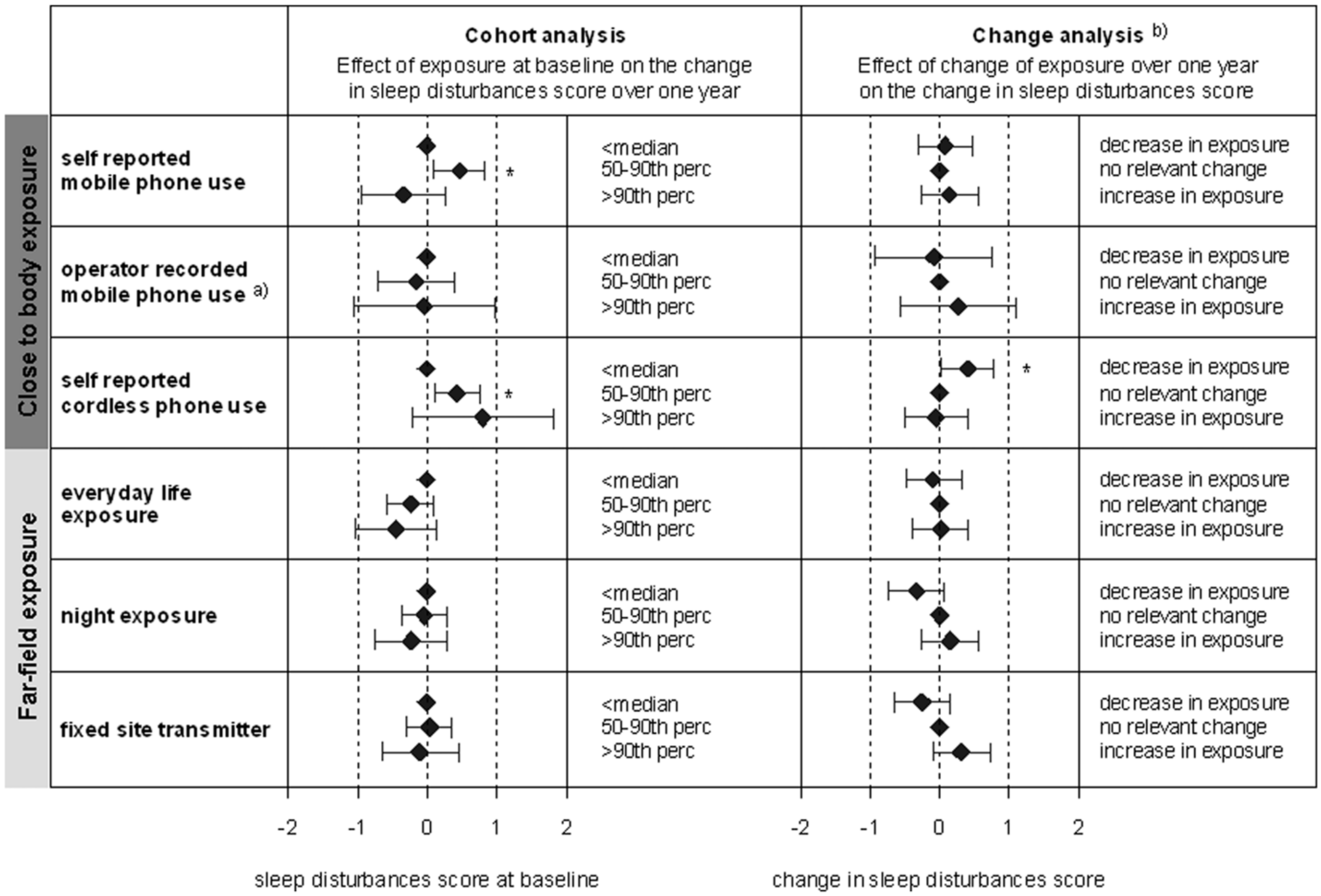


**Figure 2. Results of the longitudinal analysis sleep disturbances: Diamonds refer to the change in sleep score and the horizontal lines mark the 95% confidence intervals.** An increase in score refers to an increase in sleep disturbances. * indicates statistical significance. Confounders see Fig. 1. [a)] for a subsample of 378 (235) subjects who consented that we receive data from the operator at baseline (follow-up). [b)] In the change analysis a decrease and increase in exposure refers to the participants with the 20% largest exposure decrease and increase between baseline and follow-up survey. No relevant change includes all other participants, who experienced a smaller or no change of exposure (reference group).
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exposure source was put into operation [33]. Such an effect should have been observable with our study design.

## Conclusion

Overall, we did not find an association between self-reported sleep quality and everyday RF-EMF levels from various sources over one year. By applying a longitudinal design and using objective exposure and measured outcome data, this study increases evidence for the true absence of an effect of everyday RF-EMF exposure on sleep quality.

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## Author Contributions

Conceived and designed the experiments: MR CBF. Performed the experiments: EM PF. Analyzed the data: EM PF MR. Contributed reagents/materials/analysis tools: EM PF JF MR. Wrote the paper: EM PF JF CBF MR. Maintained and calibrated the measurement devices: JF. Contributed to the interpretation of the data analysis: EM PF JF CBF MR.

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# 5 ELECTROMAGNETIC HYPER-SENSITIVITY

# **Article 5:** Sense and sensibility in the context of radiofrequency electromagnetic field exposure

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Interactions between radiofrequencies signals and living organisms

# Sense and sensibility in the context of radiofrequency electromagnetic field exposure

## *Mesure et perception des champs électromagnétiques radiofréquences : une étude de cohorte sur l'hypersensibilité électromagnétique*

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ABSTRACT

The association between radiofrequency exposure (RF-EMF) and non-specific health complaints in electromagnetic hypersensitive (EHS) individuals was investigated in a prospective cohort study conducted between 2008 and 2009 in Switzerland. Exposure to environmental far-field RF-EMF sources was modelled and cordless and mobile phone use was also considered in the analyses. About 8% ($n = 130$) of the study population declared to be EHS. Health disturbances were considerably more prevalent in the EHS group compared to the rest of the study population. However, we did not find evidence that health disturbances of EHS individuals were associated with RF-EMF exposure.



RÉSUMÉ

L'association entre l'exposition aux champs électromagnétiques radiofréquences (RF-EMF) et les troubles non-spécifiques de la santé dont se plaignent les sujets souffrant d'hypersensibilité électromagnétique (EHS) a été étudiée dans le cadre d'une étude de cohorte prospective menée entre 2008 et 2009 en Suisse. L'exposition environnementale à des sources radiofréquences en champ lointain a été modélisée et l'usage de téléphones sans fil ou mobiles a été pris en compte dans l'analyse. Les troubles de la santé étaient considérablement plus fréquents dans le groupe des personnes EHS en comparaison avec le reste de la population étudiée. Néanmoins, nous n'avons pas mis en évidence d'association entre le niveau d'exposition aux RF-EMF et les troubles de la santé des sujets EHS.



## 1. Introduction

Nowadays, the use of wireless communication devices has become very common in our everyday lives. Wireless communication devices and stationary transmitters such as mobile phone base stations emit electromagnetic fields (EMF) in the radiofrequency (RF) range. This has raised public concerns about potential health effects [1–3]. Some individuals even attribute non-specific symptoms of ill health such as sleep disturbance or headaches to EMF exposure [2,4]. This phenomenon

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is described as electromagnetic hypersensitivity (EHS) or idiopathic environmental illness with attribution to electromagnetic fields (IEI-EMF) [5–8]. No objective diagnostic criteria for EHS has been revealed so far and little is known about effective treatment of such patients [8]. Thus, EHS status is a self-declaration based on own experience. Various definitions for EHS have been used in population based surveys to estimate the prevalence of EHS yielding prevalences of 1.5% in Sweden [9], 3.2% in California [10], 4% in the UK [11], 5% in Switzerland [2], and 8–10% in Germany [12].

A substantial part of EHS individuals (e.g. 56% in Switzerland [4]) claims to be able to perceive RF-EMF or to suffer from RF-EMF exposure immediately, or within a few minutes after exposure. This phenomenon has been investigated in a number of double-blind, randomized provocation studies by applying well-controlled exposure circumstances in a laboratory. A recent review concluded that neither perception nor development of acute symptoms was related to real RF-EMF exposure under blinded conditions [13]. Several provocation studies supported, however, the role of the nocebo effect, which means the development of adverse symptoms due to expectations (e.g. due to concerns). However, it is still not clear whether the health of EHS individuals is affected by RF-EMF exposure in the long term, i.e. after prolonged exposure to RF-EMF. To our knowledge, no epidemiological study has investigated the association between RF-EMF exposure of a few months and symptoms of ill health in an EHS collective.

We used data from a prospective cohort study on health related quality of life and radio frequency electromagnetic field exposure (QUALIFEX) to investigate the following topics:

- To compare the self-declared EHS status at baseline with the respective judgement one year later;
- To compare the socio-demography, RF-EMF exposure situation and health status of EHS individuals with the rest of the study population;
- To investigate the association between RF-EMF exposure and symptoms of ill health in an EHS collective.

## 2. Methods

### 2.1. Study population

In May 2008 we sent out questionnaires entitled “environment and health” to 4000 randomly selected residents from the region of Basel, Switzerland, aged between 30 and 60 years. To minimize non-eligibility due to language difficulties, only Swiss residents or people living in Switzerland for at least five years were selected. After one year, in May 2009, a follow-up enquiry was conducted with the respondents of the baseline survey. Ethical approval for the study was received from the Ethical Commission of Basel on March 19th, 2007 (EK: 38/07).

### 2.2. Written questionnaire

In the written questionnaire we asked about the general health status, about non-specific symptoms of ill health, about socio-demographic factors (e.g. age, gender) and about exposure relevant characteristics and behaviours. With regard to EHS, we asked the participants: “Are you electrohypersensitive?” Those answering “yes” to this question are considered electromagnetic hypersensitive (EHS). We also asked: “Do you think that you develop detrimental health symptoms due to electromagnetic pollution in everyday life?” Those answering “yes” to this questions but not declaring to be hypersensitive are called “attributers” in this paper. In the absence of a common internationally used classification scheme for EHS, we hypothesized that these two questions correspond to a different degree of involvement in the EMF topic. The term EHS is not very common in Switzerland and thus may be mainly known by persons who are already informed about EMF and health issues, whereas attributing symptoms may be associated with less prejudice towards EMF exposure. Thus, we wanted to explore whether these two groups differed in terms of sociodemographic factors, exposure situation or health status.

### 2.3. Health outcomes

We measured various somatic complaints including headache, daytime sleepiness, sleep disturbance and tinnitus by means of questionnaires.

*General health problems* were determined by using a question from the European Health Interview Survey (EHIS) Questionnaire about the general health status. Study participants who rated their general health as fair, bad or very bad were considered to suffer from general health problems in contrast to participants rating their health as good or very good.

To assess somatic complaints the *von Zerssen* somatic complaint list was used. This list consists of 24 different items covering a broad range of non-specific symptoms [14]. Severity of each symptom is assessed on a four point Likert scale (not at all, rarely, fair, heavy) resulting in a score ranging from 0 (no complaints) to 72 (severe complaints).

Severity of headache was assessed using the Headache Impact Test (*HIT-6*) [15]. HIT-6 consists of six questions using a five point Likert scale. The HIT-6 score ranges from 36 (no impact) to 78 (severe impact).

Daytime sleepiness was determined by seven items from the Epworth Sleepiness Scale (ESS) ranging from 0 (no daytime sleepiness) to 21 (very excessive daytime sleepiness) [16]. For data presentation we created a binary variable according to a previous study on insomnia [17] indicating *excessive daytime sleepiness* if the ESS score was above 10.

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The presence of *sleep disturbances* was assessed using four standardised questions from the Swiss Health Survey 2007 assessing the frequency of badly falling asleep, fitful sleeping, waking phases during night and awaking too early in the morning [18]. A binary sleep quality score was calculated by adding up all items (ranging from 0 to 12) and defining a score of eight or higher as having *sleep disturbances*.

We also asked study participants whether they suffered from *tinnitus* at the time of the survey.

### *2.4. Exposure assessment*

We assessed exposure to environmental far-field sources (e.g. mobile phone base station) as well as exposure from sources operating in close proximity to the body (e.g, mobile phone handset). Regarding exposure to environmental far-field sources, we predicted total environmental far-field RF-EMF exposure and exposure from fixed site transmitters at home separately. The latter includes exposure from mobile phone base stations and broadcast transmitters. It was modelled by means of a geospatial propagation model which had been developed and validated for the study region [19,20]. Total environmental far-field RF-EMF was obtained from a predictive exposure assessment model that was developed based on weekly personal RF-EMF measurements from 166 residents of the study area who were not part of the cohort study [21,22]. The exposure assessment model considers the following relevant exposure predictors: the modelled residential exposure from fixed site transmitters [19], modified by the type of house wall and window frames, the ownership of communication devices (W-LAN, mobile and cordless phones) and behavioural characteristics (amount of time spent in public transport vehicles or cars, percent full-time equivalent).

Regarding close to body sources we enquired the study participants about their typical use of mobile and cordless phones. In addition, we asked for informed consent to obtain operator data of their mobile phone use covering the period of the previous six month of each survey. Obviously, individuals who stated not to own a mobile phone could not provide operator data. Thus, their operator recorded use of mobile phone was set to 0 (9 EHS individuals and 9 attributers).

In order to evaluate the occurrence of information bias or a nocebo effect, we assessed self-estimated exposure to RF-EMF in comparison to the average Swiss population in the questionnaire.

### *2.5. Statistical analyses*

The prevalence of EHS for the whole study region was calculated using direct adjustments, with weights for age and gender derived from the 2008 population data of the study region by means of the survey module of STATA 10.0. Confidence intervals were calculated using the Wilson score method based on quadratic equations [23]. Comparisons between the three groups (nonsensitive individuals, attributers and EHS individuals) were done with chi-square tests in the case of binomial variables or Kruskal–Wallis tests in the case of scored or ranked data.

The association between RF-EMF exposure and health complaints was separately examined in attributers and in EHS individuals. We conducted a cohort and change analysis. In the cohort analysis, we aimed to investigate effects occurring with a latency of one year. We evaluated the association between exposure level at baseline and the change in health status between the baseline and follow-up survey. Two exposure categories were defined: exposure above median vs. exposure at median or below (reference). In the change analysis, we examined whether a change in exposure between baseline and follow-up resulted in a change of the health outcomes. We compared the study participants with the 20% largest decrease and increase in RF-EMF exposure with the remaining 60% who experienced a smaller or no change of exposure during the course of one year. For the linear outcome variables (von Zerssen-, HIT-6-, ESS- and sleep disturbance score) multiple linear regression models were calculated. For tinnitus (binary) a logistic regression model was used.

All models were adjusted for age, sex, body mass index, stress, physical activity, smoking habits, alcohol consumption, education, marital status, urban/suburban, nightshift work, use of sleeping drugs, general attitude towards the environment and whether they have moved between baseline and follow-up. Missing values in the confounder variables at baseline were replaced with the information of the follow-up and vice versa. If values were missing for both, baseline and follow-up, they were replaced with values of either the most common category (categorical variables) or with the mean value (linear variables). In all models for environmental far-field exposure sources, we included (self-reported) use of mobile and cordless phones as co-exposures. Similarly, total far-field exposure was used as co-exposure variable in all models for mobile and cordless phone use.

## 3. Results

### *3.1. EHS prevalence*

In total, 1375 persons participated in the baseline survey in 2008. This corresponds to 37% of 3763 eligible individuals invited for participation. Participation rate for the follow-up was 82% resulting in 1122 returned questionnaires. Table 1 shows the distribution of the EHS status in 2008 and 2009. Almost 70 percent of the participants stated neither to be EHS nor to attribute own symptoms to RF-EMF exposure in both surveys (defined as nonsensitive individuals). The attributer group consisted of 219 individuals (baseline and follow-up combined), and 130 study participants stated to be electromagnetic hypersensitive either in 2008 or in 2009 (EHS group). This EHS self-declaration was not very persistent: 40% stated to

**Table 1**
Overview about the EHS (electromagnetic hypersensitivity) status of the study participants in 2008 and 2009.

| | | *EHS status 2009* | | | |
|---|---|---|---|---|---|
| | | nonsensitive | attributer[a] | EHS[b] | Total |
| *EHS status 2008* | | | | | |
| nonsensitive | *n* | 773 | 85[c] | 23[d] | 881 |
| | (proportion) | (68.9%) | (7.6%) | (2.0%) | (78.5%) |
| attributer[a] | *n* | 74[c] | 60[c] | 11[d] | 145 |
| | (proportion) | (6.6%) | (5.3%) | (1.0%) | (12.9%) |
| EHS[b] | *n* | 28[d] | 16[d] | 52[d] | 96 |
| | (proportion) | (2.5%) | (1.4%) | (4.6%) | (8.6%) |
| Total | | 875 | 161 | 86 | 1122 |
| | | (78.0%) | (14.3%) | (7.7%) | (100%) |

[a] Attributes own symptoms to RF-EMF exposure.
[b] Declares to be EHS.
[c] In the following defined as attributers ($n = 219$).
[d] In the following defined as EHS individuals ($n = 130$).

**Table 2**
Comparison of the socio-demographic factors as well as self-estimated RF-EMF exposure in the three study groups.

| | Nonsensitive individuals *n* (%) | Attributers *n* (%) | EHS individuals *n* (%) | *p*-value |
|---|---|---|---|---|
| Age (years) | | | | |
| 30–39 | 219 *(28.3)* | 61 *(27.9)* | 33 *(25.4)* | 0.58 |
| 40–49 | 266 *(34.4)* | 82 *(37.4)* | 54 *(41.5)* | |
| 50–60 | 288 *(37.3)* | 76 *(34.7)* | 43 *(33.1)* | |
| Sex | | | | |
| female | 451 *(58.3)* | 133 *(60.7)* | 94 *(72.3)* | 0.01 |
| male | 322 *(41.7)* | 86 *(39.3)* | 36 *(27.7)* | |
| Urbanity | | | | |
| suburban | 487 *(63.0)* | 132 *(60.3)* | 83 *(63.8)* | 0.72 |
| urban | 286 *(37.0)* | 87 *(39.7)* | 47 *(36.2)* | |
| Educational level | | | | |
| none | 29 *(3.8)* | 20 *(9.1)* | 5 *(3.8)* | < 0.01 |
| apprenticeship | 369 *(47.7)* | 120 *(54.8)* | 76 *(58.5)* | |
| higher education | 375 *(48.5)* | 79 *(36.1)* | 49 *(37.7)* | |
| Self-estimated RF-EMF exposure in 2008[a] | | | | |
| lower | 241 *(31.2)* | 61 *(27.9)* | 33 *(25.4)* | < 0.01 |
| equal | 504 *(65.2)* | 133 *(60.7)* | 72 *(55.4)* | |
| higher | 28 *(3.6)* | 25 *(11.4)* | 25 *(19.2)* | |

[a] Compared to the Swiss population.

be EHS in both surveys, 34% only in 2008 and 26% only in 2009. Of the attributers only 27% attributed own symptoms to EMF in both surveys, the remaining individuals attributed symptoms to EMF either in 2008 (34%) or in 2009 (39%) only.

Estimated EHS prevalence in our study area in the age group of the 30–60 year old persons was 8.1% (95%-CI: 6.6% to 9.8%) in 2008 and 7.3% (95%-CI: 5.9% to 9.0%) in 2009. EHS prevalence was higher in women (8.9% in 2009) than in men (5.7% in 2009). Estimated prevalence of attributers was 13.0% (95%-CI: 11.2–15.1%) in 2008 and 14.3% (95%-CI: 12.4–16.5) in 2009.

### *3.2. Demographic characteristics of EHS individuals*

In Table 2, socio-demographic factors of EHS individuals are compared with the attributers and nonsensitive people. There were no differences between the three groups regarding the age distribution and the urbanity of their place of residence. However, the proportion of females is higher in EHS individuals than in nonsensitive persons or attributers. Non-sensitive persons are more likely to have a higher education than attributers and EHS individuals. Self-estimated exposure differed significantly between the three groups. The proportion of individuals who believed to be more exposed than the Swiss average population was 19% among EHS individuals, 11% among attributers and 4% among nonsensitive persons.

### *3.3. Exposure situation*

Fig. 1 depicts the proportion of persons owning a mobile phone, a cordless phone or a W-LAN for the three groups. There was no substantial difference between the nonsensitive and the attributer group. However, the proportion of individuals owning wireless communication devices was by trend lower in EHS individuals. This difference was most pronounced for cordless phones. Few statistical differences were observed regarding amount of use of wireless communication devices

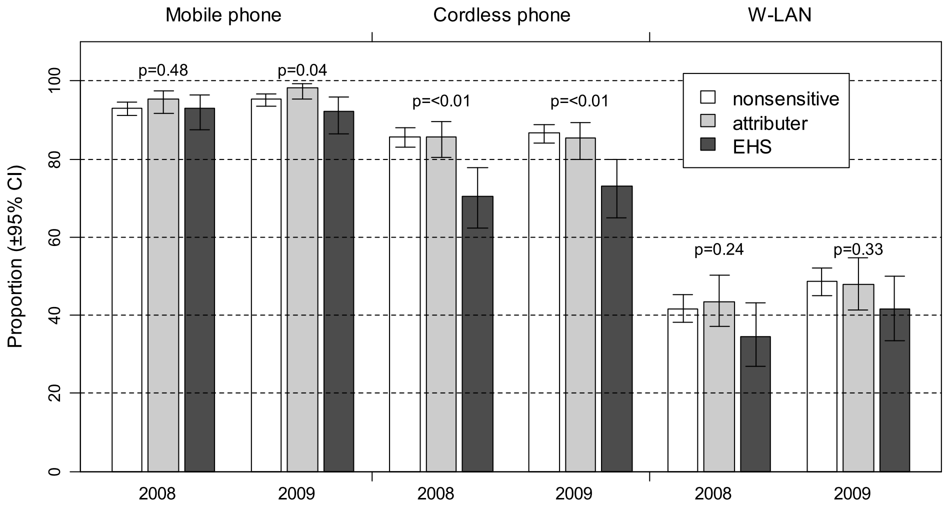


**Fig. 1.** Comparison of wireless communication device ownership between the three study groups in 2008 and 2009.

**Table 3**
Comparison of the exposure situation between the three study groups in 2008 and 2009.

| Year | *n* | Nonsensitive individuals mean | (95%-CI) | Attributers mean | (95%-CI) | EHS individuals mean | (95%-CI) | *p*-value |
|---|---|---|---|---|---|---|---|---|
| Distance to the closest mobile phone base station [m] | | | | | | | | |
| 2008 | 1122 | 290 | [276; 303] | 273 | [247; 299] | 273 | [241; 305] | 0.31 |
| 2009 | 1122 | 294 | [279; 310] | 286 | [256; 316] | 269 | [237; 301] | 0.39 |
| Predicted residential exposure to fixed site transmitters [mW/m$^2$] | | | | | | | | |
| 2008 | 1122 | 0.020 | [0.017, 0.024] | 0.033 | [0.017, 0.049] | 0.015 | [0.011, 0.019] | 0.29 |
| 2009 | 1122 | 0.020 | [0.016, 0.024] | 0.037 | [0.020, 0.055] | 0.017 | [0.011, 0.022] | 0.13 |
| Predicted total environmental far-field exposure (all sources) [mW/m$^2$] | | | | | | | | |
| 2008 | 1122 | 0.120 | [0.117; 0.123] | 0.126 | [0.118; 0.134] | 0.114 | [0.107; 0.121] | 0.42 |
| 2009 | 1122 | 0.125 | [0.122; 0.128] | 0.134 | [0.126; 0.141] | 0.116 | [0.108; 0.123] | 0.02 |
| Self-reported use of mobile phone [min/week] | | | | | | | | |
| 2008 | 1119 | 62.9 | [52.4; 73.3] | 81.1 | [58.8; 103.3] | 55.8 | [35.3; 76.31] | 0.40 |
| 2009 | 1113 | 62.5 | [52.1; 72.8] | 90.0 | [64.8; 115.1] | 61.6 | [38.4; 84.7] | 0.01 |
| Operator registered use of mobile phone [min/week] | | | | | | | | |
| 2008 | 458 | 24.3 | [19.3; 29.3] | 34.1 | [19.0; 49.2] | 44.0 | [21.0; 67.0] | 0.28 |
| 2009 | 423 | 17.7 | [14.0; 21.4] | 29.0 | [17.2; 40.8] | 26.9 | [13.7; 40.2] | 0.07 |
| Self-reported use of cordless phone [min/week] | | | | | | | | |
| 2008 | 1119 | 74.5 | [66.9; 82.1] | 79.6 | [62.3; 96.9] | 69.8 | [49.8; 89.8] | 0.16 |
| 2009 | 1110 | 77.6 | [69.0; 86.3] | 79.5 | [62.9; 96.1] | 65.9 | [47.7; 84.0] | 0.10 |

(Table 3). In tendency, EHS and nonsensitive individuals showed a similar usage pattern, whereas attributers tended to use wireless communication devices more often. Distance of residency to the closest base station as well as predicted residential exposure from fixed site transmitters was not different between the three groups. Predicted total far-field exposure from all sources was somewhat lower for the EHS group.

The 34 study participants who became EHS between 2008 and 2009 tended to reduce their use of wireless communication devices between baseline and follow-up (mobile phone: −4.3 min [95%-CI: −24.6, 16.0 min], cordless phones: −2.4 min [95%-CI: −27.7, 22.9 min]). In contrast, 44 study participants who lost the EHS status between 2008 and 2009 tended to increase their use of wireless communication devices (mobile phone: +10.7 min [95%-CI: −8.7, 30.0 min], cordless phones: +2.4 min [95%-CI: −27.0, 31.9 min]).

### *3.4. Health status*

General health problems and sleep disturbances were least frequent in the nonsensitive group and most frequent in the EHS group (Fig. 2). Frequency of tinnitus was also somewhat higher among EHS, although not statistically significant. Regarding excessive daytime sleepiness, little differences between the three groups were observed. A substantial difference in the von Zerssen and the HIT-6 score was observed between the three groups. In 2009, mean von Zerssen score was 12.4 [95%-CI: 11.8, 13.1] in the nonsensitive group, 13.7 [95%-CI: 12.4, 15.0] in the attributer group, and 17.2 [95%-CI: 15.3, 19.1] in the EHS group. In 2009, mean HIT-6 score was 44.8 [95%-CI: 44.2, 45.3] in the nonsensitive group, 47.1 [95%-CI: 45.9,

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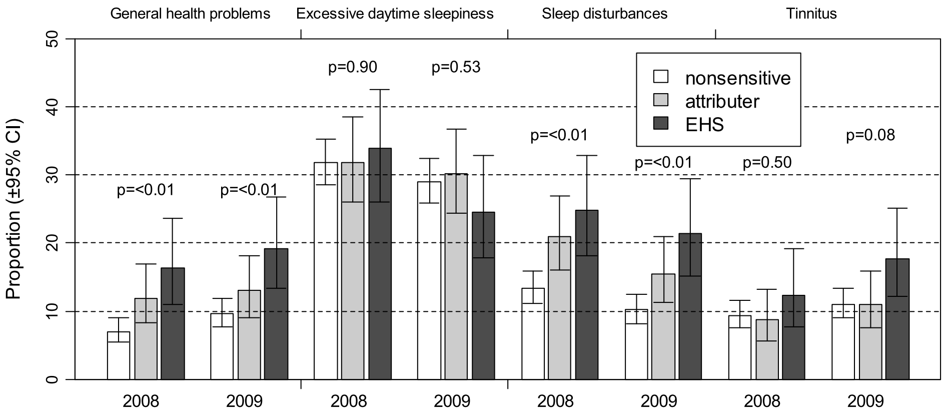


**Fig. 2.** Frequency of various health problems in the three study groups in 2008 and 2009.

**Table 4**
The association between the von Zerssen score and various exposure surrogates for the EHS group ($n = 130$). The table shows the change of the von Zerssen score (including 95% confidence interval) for various exposure groups compared to the reference group. The cohort analyses refer to the exposure at baseline (i.e. one year latency), the change analyses refer to the exposure change between baseline and follow-up.

| | Cohort analysis | | Change analysis | | |
|---|---|---|---|---|---|
| | ⩽median (reference) | >median (95%-CI) | Exposure decrease (95%-CI) | No change (reference) | Exposure increase (95%-CI) |
| Environmental far-field exposure | | | | | |
| Total environmental far-field exposure | 0 | −0.50 [−4.12; 3.11] | 3.61 [−0.32; 7.53] | 0 | 2.90 [−1.15; 6.95] |
| Residential exposure to fixed site transmitters | 0 | −2.04 [−5.06; 0.97] | **−5.65 [−9.66; −1.65]** | 0 | −0.03 [−4.19; 4.13] |
| Close to body exposure | | | | | |
| Mobile phone use (self-reported) | 0 | 1.64 [−1.95; 5.23] | −1.37 [−5.46; 2.73] | 0 | 2.39 [−1.52; 6.29] |
| Mobile phone use[a] (operator data) | 0 | 1.75 [−3.28; 6.77] | −0.65 [−6.73; 5.44] | 0 | 1.94 [−5.68; 9.56] |
| Cordless phone use (self-reported) | 0 | 0.16 [−2.94; 3.26] | 0.87 [−3.22; 4.95] | 0 | 0.37 [−4.53; 5.27] |

All regression coefficients are adjusted for: age, sex, body mass index, stress, physical activity, smoking habits, alcohol consumption, education, marital status, urban/suburban, nightshift work, use of sleeping drugs, general attitude towards the environment and moving between baseline and follow-up.
[a] Operator data were obtained for 50 EHS individuals at baseline (cohort analysis) and for 36 EHS individuals for both surveys (change analysis).

48.2] in the attributer group, and 48.1 [95%-CI: 46.4, 49.8] in the EHS group. Change of the EHS status was associated with a corresponding change of the health scores. For instance, the von Zerssen score increased by 3.5 units [95%-CI: 1.0, 6.0] for those becoming EHS and decreased by 3.3 unit [95%-CI −5.8, −0.9] for those losing the EHS status between 2008 and 2009. The corresponding changes of the HIT-6 score were +1.75 [95%-CI: −0.25, 3.75] and −0.7 [95%-CI: −3.5, 2.0], respectively.

### *3.5. Association between exposure and health*

Table 4 shows the association between the von Zerssen score and various exposure proxies in the EHS group. All coefficients were statistically non-significant except a drop of the von Zerssen score by 5.5 units in the EHS individuals with the 20% largest reduction of residential RF-EMF exposure from fixed site transmitters between 2008 and 2009. However, an increase of fixed site transmitter exposure between 2008 and 2009 was not related to an increase in the von Zerssen score (regression coefficient: −0.03) and also being in the high exposure group at baseline (>median) was not followed by an increase in the von Zerssen score, but rather by a decrease of the score by 2.0 units [95%-CI: −5.1; 1.0]. Self-estimated exposure was not associated with the von Zerssen score (data not shown).

The same analyses as presented in Table 4 were done for the HIT-6, the ESS and the sleep disturbance score (data not shown). Out of these 45 additional regression models, five statistically significant regression coefficients were observed. However, these significant effects referred to different outcomes and different exposure measures: an increase in the ESS score in relation to an increase of the total far-field exposure, a decrease of the ESS score in relation to a decrease of the residential fixed site transmitter exposure, an increase in the sleep disturbance score in relation to a decrease in self-reported as well as recorded mobile phone use, and a decrease of the HIT-6 score in relation to be a heavy cordless phone user at baseline.

All analyses were repeated for the attributers resulting in three significant regression coefficients out of 60 models. (This concerned a decrease of the von Zerssen score with a decrease in the operator recorded mobile phone use between 2008 and 2009; a decrease of the ESS score in those attributers who were heavy cordless phone user at baseline; and an increase in the sleep disturbance score for the 20% attributers who reported the largest increase of cordless phone use between 2008 and 2009.)

A pooled analysis of the EHS and the attributer group did not yield substantially different results (data not shown) and also analyses restricted to the 52 participants, who stated to be EHS in both surveys, did not provide support for an exposure effect. Tinnitus was not related to any of the considered exposure metrics, neither in the EHS nor in the attributer group (data not shown).

## 4. Discussion

About 7–8% of our study population declared to be EHS in 2008 and 2009 and about 13–14% attributed own symptoms to RF-EMF exposure but did not declare to be hypersensitive (attributers). However, only a minority of the EHS individuals and the attributers made the same declaration in 2008 and 2009. The RF-EMF exposure situation of EHS individuals was comparable to the rest of the population except ownership of cordless phones. Health disturbances were considerably more prevalent in the EHS group than in the attributer group and even more than in the rest of the population. Most importantly, we did not find evidence that various symptom scores were associated with RF-EMF exposure in the EHS group.

### *4.1. Strengths and limitations*

To our knowledge, this is the first epidemiological study investigating the association between health related quality of life and RF-EMF exposure in an EHS collective. Due to the cohort design we were able to capture health effects with a one year latency. Our previous measurement study demonstrated that the average weekly personal RF-EMF exposure remains relatively stable over several months [22]. Thus, this cohort study allowed investigating health effects of considerable longer exposure duration than in human experimental studies. We considered both, exposure to environmental far-field sources as well as exposure to sources close to the body. For both types of exposure, we used objective data. The elaborate prediction model for the total far-field exposure includes all relevant RF-EMF exposure sources in everyday life in the frequency range of 88–2500 MHz. The prediction model is based on a geospatial propagation model, which uses accurate parameters from all fixed site transmitters of the study region. In addition, the prediction model considers also exposure relevant behaviours that were identified in a previous study by personal exposure measurements and subsequently asked in the health study by questionnaire. The feasibility and reproducibility of the prediction model as well as of the geospatial propagation model was demonstrated [19,21]. For those who consented to provide the mobile phone operator data, we collected traffic records of all ingoing and outgoing calls of the previous six months of each survey from the mobile phone operators, which has, to our knowledge, not been done in previous studies investigating the effect of mobile phone use on the development of non-specific symptoms. Although self-reported, the subjective symptoms that we assessed were based on standardized questions.

A limitation was the rather low participation rate of 37% in the baseline survey. As a consequence, our estimated EHS prevalence is uncertain. One might assume that study participants may be generally more concerned or affected by EMF than non-responders resulting in an overestimation of the EHS prevalence. Interestingly, this was not confirmed in a non-responder survey that we conducted with 665 non-responders of the baseline survey by phone. In this non-responder survey, EHS prevalence was 15.9%. Thus, it is difficult to know at present, whether the estimated EHS prevalence of 7–8% is an over- or underestimation of the true EHS prevalence of the 30–60 year old people living in the study region. In 2004, a representative Swiss telephone survey concluded that EHS prevalence was 5% among people older than 14 years [2]. The low participation rate of the baseline survey is less of a problem for the cohort and change analysis because participation rate was high in the follow-up (82%).

Another limitation is the relatively small sample size. The EHS group consisted of 130 individuals and the attributer group of 219 persons. Thus, the power of the study was relatively low and subtle effects may have been missed.

Exposure levels were low in our study and we observed only small exposure differences between baseline and follow-up. This represents the current RF-EMF exposure situation in the everyday environment. This implies that our study is informative for exposure levels that are experienced nowadays. However, we cannot draw conclusions about health consequences for EHS individuals at levels close to the exposure limits, which are much higher.

### *4.2. Interpretation*

Observational research in EHS individuals is limited if one assumes that EHS individuals tend to avoid EMF exposure. If such an intentionally achieved exposure reduction results in a better health status, it could either be mediated by a biophysical mechanism or by a pure nocebo mechanism. Interestingly, four out of six significant EHS effects concerned the exposure reduction in the change analyses. Thus, the question arises whether exposure avoidance behaviour is relevant for these findings. We observed a decrease of wireless communication usage for individuals that became EHS during the course of the study and an increase in exposure for those who lost the EHS status. These trends were weak and not statistically significant. We did not find such trends for the distance between the closest mobile phone base station and place of residence, nor for the modelled residential exposure to fixed site transmitters. Thus, EHS individuals seem not to have moved due to the presence of a mobile phone base station during the course of the study. Overall the exposure situation of EHS individuals differed not much from the rest of the study population (except ownership of cordless phones) suggesting that exposure avoidance behaviour is not pronounced.

In order to identify the potentially most sensitive individuals we asked about two different aspects in this context: (i) to attribute own symptoms to EMF (attributers); and (ii) to declare to be EHS. We hypothesized that attributers have a less prejudiced attitude to EMF than persons who declare to be EHS because the term EHS is not very common in Switzerland. A less prejudiced attitude to EMF may be associated with less exposure avoidance behaviour and thus, if there is any health effect at all, there might be a higher chance to detect such an effect in this group by means of an observational study. In fact, in none of the two groups we found evidence for health effects from EMF, however, we found differences between these two groups with respect to socio-demography, to RF-EMF exposure and to health status. This suggests that the methods of EHS classification matters and these should be considered in future studies, in risk communication or in the management of patients. Also a German interview based study observed considerably heterogeneity within the EHS group in terms of significance and coping with the perceived sensitivity in their daily life [24] and a Scandinavian study observed differences between people with symptoms related to mobile phone and people with general EHS [25]. Potentially one could use biological measures to differentiate between various EHS subgroups. For instance, altered cortical excitability [26], different heart rate variability [27,28], altered skin conductance [29], or different electrodermal activity [28] were observed in EHS individuals compared to the rest of the population. These parameters were not related to EMF exposure but may indicate that EHS individuals suffer from a general higher genuine vulnerability to physical and psychosocial environmental stressors.

Of note is the relatively small overlap between the EHS declaration in 2008 and 2009. This suggests that for most of the EHS individuals the perceived impairment is relatively subtle and only a small minority feels heavily affected by RF-EMF exposure. This corresponds to our experience with a medical helpdesk for EHS patients in Switzerland. During two years, only about 150 patients contacted the helpdesk for advice and thereof only about 50 patients were subsequently sent to a medical doctor. The generally low affliction may explain why the exposure situation of EHS individuals was not markedly different from the rest of the population. Only ownership of cordless phones was significantly lower in the EHS group. The attributer group tended to use wireless communication devices even more often than the rest of the population.

Regarding the association between symptoms and RF-EMF exposure, we observed only few statistically significant effects, which were not consistent with respect to exposure source or health effects. Some of the observed exposure effects were even positive for health. Given the numerous analyses we performed, a few statistically significant effects can be expected by chance. We conducted numerous analyses because in the absence of a known biological mechanism in the low dose range, it was unclear which aspect of exposure might be relevant for health disturbances, if any at all. In our analyses, we did not apply a formal multiple endpoint correction (e.g. Bonferroni correction). Instead we checked the consistency and biological plausibility of similar analyses. We hypothesized prior to the conduct of the analyses that exposure at the head, mainly caused by mobile and cordless phones, is most relevant for headache; total environmental far-field exposure is particularly relevant for the von Zerssen somatic symptom score; and residential exposure from fixed site transmitters, which also occurs during night, may play a role for ESS and sleep disturbances. However, none of these associations were observed. We neither observed similar results for one specific outcome from similar acting exposure measures (e.g. similar effects from mobile and cordless phone use) nor from similar models (e.g. cohort and change analysis). Thus, we conclude that the observed statistically significant effects occurred by chance and our study provides little evidence for detrimental health effects due to RF-EMF exposure for EHS individuals. Nevertheless, we cannot completely exclude that one or some of the observed patterns are real, even if formal significance criteria are not met. However, this has to be confirmed in an independent study.

Inherently, the absence of a phenomenon cannot be proven with empirical research. Thus, we cannot completely rule out that there exist a small minority who are particularly sensitive to EMF exposure. However, such individuals have not yet been identified [6] and our study demonstrates clearly that, as a group, EHS individuals are not more vulnerable to RF-EMF exposure than the rest of the population.

The observed lack of association between RF-EMF exposure and health symptoms is in line with the results from provocation studies investigating the acute development of symptoms in EHS individuals [13]. Interestingly, our previous measurement study demonstrated that self-estimated RF-EMF exposure is not related to actual RF-EMF exposure [30]. On one hand this means that our study participants are actually blinded to their exposure status which prevented our analyses from information bias. On the other hand comparing self-estimated exposure with health scores allows evaluating potential nocebo effects. EHS individuals tended to believe that their exposure was higher than the rest of the population, but their self-estimated exposure was not associated to various health disturbances. Thus, nocebo seems to play a minor role in our data. This is in contradiction to provocation studies where nocebo played a relevant role for the development of acute health problems [13].

In conclusion, our study could not confirm an association between RF-EMF exposure in the everyday environment and health disturbances for EHS individuals or for people attributing own symptoms to RF-EMF exposure. This study has captured an exposure duration of one year and is in line with the results from provocation studies that have investigated acute effects of RF-EMF exposure in EHS individuals.

## 5. Conflict of interests

The authors declare that they have no competing financial interests.

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# 6 SUMMARY OF THE MAIN FINDINGS

In this chapter, the results of this thesis are summarized according to the aims outlined in chapter 1.2. The detailed results are described in the respective articles in chapter 3-5.

### *A) To evaluate and apply an appropriate exposure assessment method*

⇒ ***Evaluation of a standardized study protocol to measure personal RF-EMF exposure***

In the process of evaluating a standardized study protocol, we identified two different types of personal measurement surveys:

- Population survey: determination of personal exposure distribution
- Micro environmental measurements: determination of typical exposure levels in different microenvironments, e.g. public transport

For study instruments, study procedures and statistical analyses, we suggested the following most important requirements:

- Study instruments:
    - o Currently, the best personal measurement device on the market is the exposimeter “EME Spy 140” from Satimo, France.
    - o The use of an easily comprehensible and simple time activity diary is recommended.

    - o Questionnaire about exposure relevant factors are useful for interpreting the data.
- Study procedures:
    - o Measurement durations between one and seven days for population surveys are recommended.
    - o Selection of study participants should ideally happen randomly for population surveys and for micro environmental measurements highly motivated study assistants should perform the measurements.
    - o Handling of the exposimeter must be explained to the participants.
    - o Maintenance and calibration of the devices should occur regularly to ensure measurement accuracy.
    - o For data analysis (especially for summary statistics) and to correctly take into account the values under the detection limit, the use of the ROS methods is suggested.

⇒ ***Exposure assessment in the QUALIFEX project***

Mean weekly exposure of all 166 participants of the exposimeters study was 0.22 V/m (range: 0.07 – 0.58 V/m). Total exposure was mainly due to mobile phone base stations, mobile phone handsets and cordless phones. In order to evaluate our exposure assessment methods which we used in the health study, we correlated predicted exposure at home from the geospatial propagation model with the corresponding measured mean exposure during one week. The rank correlation was with 0.72 strong. Correlation between full exposure prediction model and measured mean exposure during one weak was 0.51 (95%-CI 0.39–0.61). To assess exposure to close to body sources, information about self-reported mobile phone use and operator data was used from the QUALIFEX health study. Rank correlation between operator data and self-reported mobile phone use was 0.78.

### B) To investigate the association between RF-EMF exposure and self-reported sleep quality and sleep behaviour

⇒ ***Cross-sectional study (baseline analyses)***

A total of 1375 people completed the baseline questionnaire. This corresponds to a response rate of 37%. Mean age (standard deviation) of the study participants was 46 (± 9) years and more females (58%) participated. Based on the full exposure prediction model, mean and median everyday life exposure was 0.18 V/m for all included study participants. Our analyses did not indicate an impairment of self-reported sleep quality due to exposure from various sources of RF-EMF in everyday life. Compared to the rest of the study population, the 10% most exposed participants in everyday life had an estimated risk for sleep disturbances of 1.11 (95% CI: 0.50 to 2.44) and for excessive daytime sleepiness of 0.58 (95% CI: 0.31 to 1.05). Also, the use of mobile and cordless phones was not associated with a decrease in self-reported sleep quality. Non-responder analyses revealed no substantial differences between responders and non-responders.

⇒ ***Longitudinal study***

In total 1125 subjects filled in the follow-up questionnaire in May 2009 (response rate 82%). Generally, the characteristics of the study participants in the baseline survey and in the follow-up survey were comparable. There were only very small changes in exposure levels over the one year study period. Overall, our analyses did not indicate effects of longitudinal exposure (one year) on self-reported sleep quality. An increase of everyday life exposure between baseline and follow-up did neither result in increased daytime sleepiness (score change: 0.23 units (95%-CI: -0.26 to 0.71) nor increased sleep disturbances (0.09 units (95%-CI: -0·31 to 0.48). Operator-recorded and self-reported mobile phone use was not associated with self-reported sleep quality.

⇒ ***Nested sleep study***

Measurements with the actigraphic device were obtained from 120 study participants during 1484 nights overall. Mean sleep duration was 6.9 hours (h) during weekdays (range: 3.9 h to 11.5 h) and 7.8 h during weekends (range: 3.2 h to 13.1 h). Sleep efficiency was 91.0 % (range: 79.0% to 96.9%) on average. Generally, women slept longer than men and had a better sleep efficiency. Exposure in the sleeping room during night was on average 0.20 V/m. There was no association between total night-time exposure, exposure from fixed site transmitters, or total exposure during one day and sleep duration as well as sleep efficiency.

### *C) To evaluate associations between RF-EMF exposure and electromagnetic hypersensitivity*

Out of 1125 returned questionnaires in the follow-up survey, 130 study participants stated to suffer from electromagnetic hypersensitivity either in 2008 or in 2009 (EHS group). The group of symptom attributers consisted of 219 individuals (baseline and follow-up combined). Estimated EHS prevalence was 8.1% (95% CI: 6.6% to 9.8%) in 2008 and 7.3% (95% CI: 5.9% to 9.0%) in 2009. There was no difference between the three groups (EHS, attributer and nonsensitives) regarding age distribution. The proportion of females was higher in EHS individuals than in nonsensitive persons or attributers. The proportion of individuals who believed to be higher exposed than the Swiss average population was 19% among EHS individuals, 11% among attributers and 4% among nonsensitive persons. In general, we observed similar usage patterns for wireless communication devices in EHS and nonsensitive individuals, whereas attributers tended to use wireless communication devices more often than the two other groups.

General health problems and sleep disturbances were most frequent in EHS individuals. However, our analyses do not suggest an association between RF-EMF exposure and various health symptom scores in the EHS group.

# 7 GENERAL DISCUSSION

Specific aspects of the different aims are discussed in the corresponding articles. In the following, more general aspects are illustrated and the results of our analyses are put in context with other studies addressing possible health hazards of RF-EMF. The strength and limitations of the QUALIFEX project are described in detail and the public health relevance of our study and its findings is discussed at the end of this chapter.

## 7.1 Discussion of the exposure assessment method

One aim of this dissertation was to apply and evaluate an appropriate exposure assessment method. Therefore we compared measurements of the exposimeter study with the prediction models which were developed based on these measurements (Bürgi et al. 2010; Frei et al. 2009a). The results are discussed in Article 2 and showed a fairly good correlation. The model was validated with 31 study participants, who carried an exposimeter during two weeks and whose second week measurements had not been used for the development of the model. High correlations were found for this group (Spearman correlation coefficient: 0.75; 95%-CI 0.53–0.87) (Bürgi et al. 2010; Frei et al. 2009a). However, one problem was that we did not have the opportunity to validate our models in an independent study sample.

In the nested sleep study, we measured RF-EMF exposure with the exposimeter during one week. The exposimeter was placed in the sleeping room near the bed and on one day, participants were asked to carry around the exposimeter during their normal daily activities. These measurements gave us the opportunity to validate our prediction models which we had used in the health study (cross-sectional and longitudinal study) in an independent sample. For the 120 participants who participated in the nested sleep study, we could predict exposure values with the full exposure prediction model (total exposure), with the night model (night exposure) and with the geospatial propagation model (fixed site transmitters). In *Table 7.1* the Spearman correlation coefficients for the correlations between measurements and the predicted exposure values are presented. These correlations varied between no correlation (-0.04) and a moderate correlation (0.41). The acceptable coefficient of 0.41 was calculated for the correlation between measurements of fixed site transmitters in the sleeping room and the geospatial propagation model. We observed no correlation between one-day measurements and the full exposure prediction model (total exposure). Additionally, the correlation between the night model and measurements in the sleeping room was quite low.

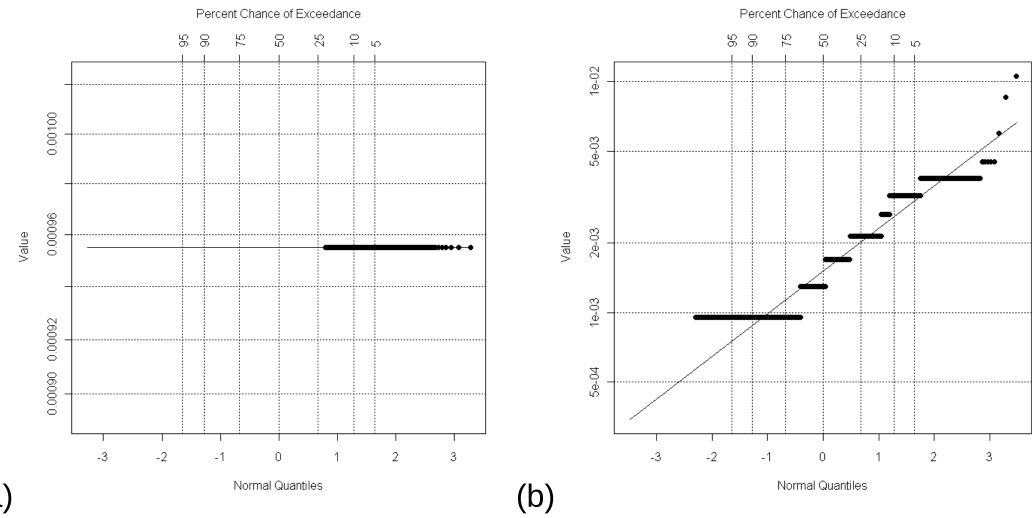
***Table 7.1*** *Spearman rank correlations of the exposimeter measurements and the prediction models (night and total exposure) and the geospatial propagation model (fixed site transmitter). Correlation coefficients in bold indicate that the model and the measurements relate to the same exposure parameter.*

| **Prediction/ calculation** / **Measurements** | **Night exposure** (predicted) | **Fixed site transmitter** (modelled) | **Total exposure** (predicted) |
|---|---|---|---|
| **Sleeping room** (night measurements) | **0.25** | 0.31 | 0.04 |
| **Sleeping room** (measured fixed site) | 0.33 | **0.41** | 0.07 |
| **1-day measurements** | -0.04 | 0.07 | **0.07** |

The following points might be reasons for the low correlations between measurements and predicted values:

- The full exposure prediction model (total exposure) was developed based on measurements over one week. The participants of the sleep study carried around the exposimeter during one day only. Therefore, less data about everyday life exposure was obtained. It might be that exposure in everyday life is not sufficiently represented in one-day measurements.

- The lower detection limit of the exposimeter is at 0.05 V/m and a large proportion of measurements were below that value. Therefore, mean values were calculated using the regression on order statistics (ROS) (Röösli et al. 2008). In this method, summary statistics are calculated by fitting a certain distribution to the detected values, in our case a lognormal distribution. During the analyses, we observed that no reliable summary statistics can be computed with the ROS method if all detected measurements in one frequency band are of the same value. In this case, ROS fits a horizontal line to these values and estimates all nondetects to the same value. *Figure 7.1* shows an output of a ROS calculation for a specific frequency band. We included a security loop in our R program in order for ROS to substitute these unreasonable mean values with more reasonable values based on experience instead.




(a) (b)

***Figure 7.1:*** *Output of a ROS calculation for one subject and one frequency band. Left panel shows an example where all measured data had the same value (a) and on the right hand side an example (b) with lognormally distributed values. Black dots represent detected values. The black line indicates the fit.*

- At the time point of the measurements for the sleep study, the exposimeters already showed some signs of age. Some frequency bands, especially UMTS (Universal Mobile Telecommunication System) and W-LAN frequencies, showed a permanent background noise. An example of such a measurement with background noise is presented in *Figure 7.2*. We tried to correct this by virtually increasing the detection limit for frequency bands where this problem was observed.

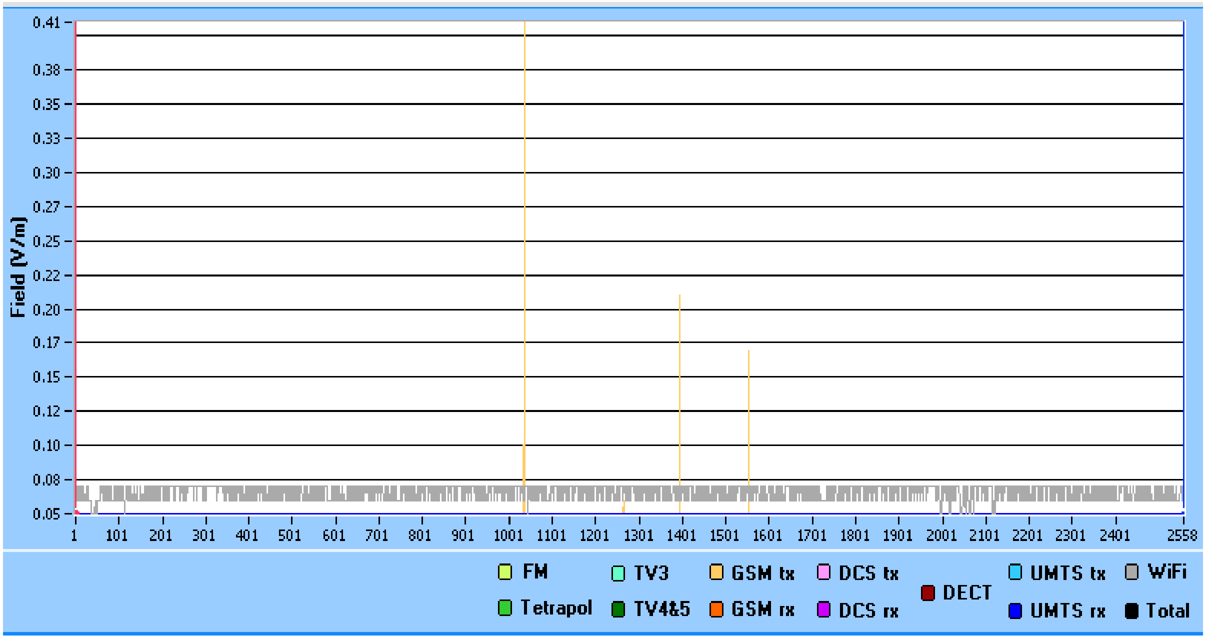



***Figure 7.2:*** *Example of an exposimetric measurement with background noise in the WiFi band (grey colour). In this case, in the ROS script, the detection limit was virtually increased to 0.08 V/m.*

The above mentioned problems with the measurements and exposimeters (symptoms of old age) were more pronounced in the sleep study than in the exposimeter study, based on which the full exposure prediction model was developed. In general, number of measurements were lower in the sleep study (n=120) and therefore the estimation of mean values even more problematical. All mentioned problems might have contributed to the low correlations of the full exposure prediction model with the measurements in the nested sleep study.

***Implications for further studies***

The validation of the full exposure prediction model with exposure data of the nested sleep study showed that exposure assessment, especially of far-field sources, remains a difficult issue in conducting epidemiological studies.  A combination of such prediction models for far-field exposure with exposure information of close to body sources, as we did in the health study, is a good approach and all relevant exposure sources are included. Of course, further improvement in modelling personal exposure has to be done. Our full exposure prediction model might be influenced by a few highly exposed participants of the exposimeters study and another study population might lead to different results and different exposure relevant predictors (Frei et al. 2009a). Moreover, prediction models must be adapted to the personal behaviours of the study participants, to the local conditions in the study region and to new technologies like the 4$^{th}$ mobile phone generation LTE (Long Term Evolution). Another improvement will be achieved by using the new model of the Satimo exposimeters. The detection limit of this new device was lowered to 0.005 V/m for some frequency bands. In addition, an increased frequency range (80 MHz – 6 GHz) was implemented and the storage capacity has been improved. Together with our suggestions for a standardized study protocol in future population based surveys (cf. Article 1), more robust data can be gained, exposure data quality will be increased and measurement uncertainty will be reduced. Applying such common core procedures in future personal measurement studies are necessary in order to make sure that observed differences reflect real exposure differences and are not due to differences in methodological aspects.

## 7.2 Assessment of sleep quality and sleep behaviour

To assess subjective sleep quality in our health study, we used the Epworth sleepiness scale (ESS) und four standardized questions from the Swiss Health Survey (SHS). ESS score assesses daytime sleepiness and distinguishes between normal subjects and patients with obstructive sleep apnea syndrome and idiopathic hypersomnia (Johns and Hocking 1997). The questions from the SHS give more information on insomnia. The advantages of these two scores were that they are quite concise, standardized and assess two different aspects of sleep quality. A disadvantage of the scores was that we did not have information on sleep duration and no other sleep parameters in the baseline and follow-up surveys. This additional information would have given us the opportunity to look in more details in the subjective sleep quality. In the nested sleep study, we therefore used the Pittsburgh Sleep Quality Index (PSQI). The PSQI score gives more information on sleep behaviour and sleep habits than the other two scores, but is longer and more time-consuming to fill in and therefore less comfortable for the study participants in questionnaire surveys.

In the nested sleep study we used actigraphic measurements to assess sleep behaviour. This method was validated in various studies with polysomnographic measurements, which are defined as the gold standard. These studies showed that several sleep parameters correlated fairly well with polysomnographic measurements (Ancoli-Israel et al. 2003; Sadeh and Acebo 2002). Sleep efficiency and sleep duration are accurately represented with the actigraphic measurements compared to the polysomnography (PSG). In a validation study of Kushida et al. (2001) sleep efficiency and total sleep duration measured with the actigraph did not significantly differ from PSG measurements. Generally, sleep latency showed to be poorly assessed by actigraphic measurements. A reason for the low correlation between PSG and actimetric measurements is that actigraphy records movements of the limbs (normally of the arms). Just lying in the bed, not sleeping and trying to fall asleep leads not compulsorily to limb movements and sleep latency is therefore erroneously estimated.

To gather information on validity and reliability of our sleep parameters, we compared actigraphic measurements with self-reported data of the PSQI (*Table 7.2*). Mean time in bed and mean sleep efficiency were very similar for actigraphic measurements and self-reports. As we expected, sleep latency was longer with subjective data than with actigraphic measurements. As a consequence of the uncertainty of this information, we did not include this parameter in our final analysis. But for internal use, we calculated if exposure influences sleep latency (actigraphic measurements and self-reports). The results showed that neither actigraphic nor self-reported sleep latency was associated with exposure to RF-EMF. Total time in bed and sleep efficiency was similar for actigraphic measurements and self-reported data. Assumed sleep duration was longer based on objective data than on self-reported data. The difference of 36 minutes between objective data and self-reported sleep duration can not only be explained with the underestimation of the sleep latency with the actigraphic device. This overestimation of sleep duration with actigraphy was also observed in a study of de Souza et al. (2003). The overestimation of the total sleep duration might be a direct consequence of the limited capacity of the actigraphy to identify waking periods. The main reason for this overestimation might be that subjects who wake up can remain motionless and therefore actigraphy cannot record all wake phases.

***Table 7.2:*** *Comparison of objective and subjective sleep parameters. All values are mean values and data were collected in the nested sleep study (n=120).*

| | **Objective data (Actigraphy)** | **Self-reported data (Pittsburgh Sleep Quality Index)** |
|---|---|---|
| Time in bed (h) | 7.6 | 7.5 |
| Sleep efficiency (%) | 91.0 | 91.3 |
| Sleep latency (min) | 4.6 | 13.4 |
| Assumed sleep duration (h) | 7.4 | 6.8 |

The recording time of two weeks might have been too short. For organizational and financial reasons a longer recording time was not possible in our study. In field intervention studies, sleep behaviour was recorded during 12 nights (Danker-Hopfe et al. 2010). So far, the nested sleep study is to my knowledge the first study which objectively measured sleep behaviour and exposure to all relevant RF-EMF sources during two weeks in a rather large sample size. Additionally, the nested sleep study confirmed our results of the cross-sectional analyses (Article 3) where we had predicted exposure values and self-reported data on sleep quality.

## 7.3 Comparison with other findings in the literature

In the QUALIFEX project, we found neither in our cross-sectional analyses (Article 3) nor in the longitudinal analyses (Article 4) evidence for an association between exposure to RF-EMF and effects on sleep. These findings were confirmed with objective data on exposure and sleep in the nested sleep study (Article 4).

We used a very comprehensive exposure assessment method, included all relevant factors and we applied a cohort design. We could not detect an effect of RF-EMF exposure on self-reported sleep quality and sleep behaviour. Our findings are in line with most of the previous, cross-sectional epidemiological studies (Berg-Beckhoff et al. 2009; Hutter et al. 2006; Kühnlein et al. 2009; Thomas et al. 2008) where RF-EMF exposure was assessed using spot measurements or short-term measurements. Only in an Egyptian study (Abdel-Rassoul et al. 2007), about a twofold increased risk for sleep disturbances for people who work near a mobile phone base station was found. However, this study was most likely biased because exposure was neither modelled nor measured. In addition, it is unclear how participants were recruited and selected and it is highly possible that participants were aware of their exposure status.
Field-intervention studies did also not yield evidence for a true relation between RF-EMF exposure and sleep quality (Danker-Hopfe et al. 2010; Leitgeb et al. 2008).

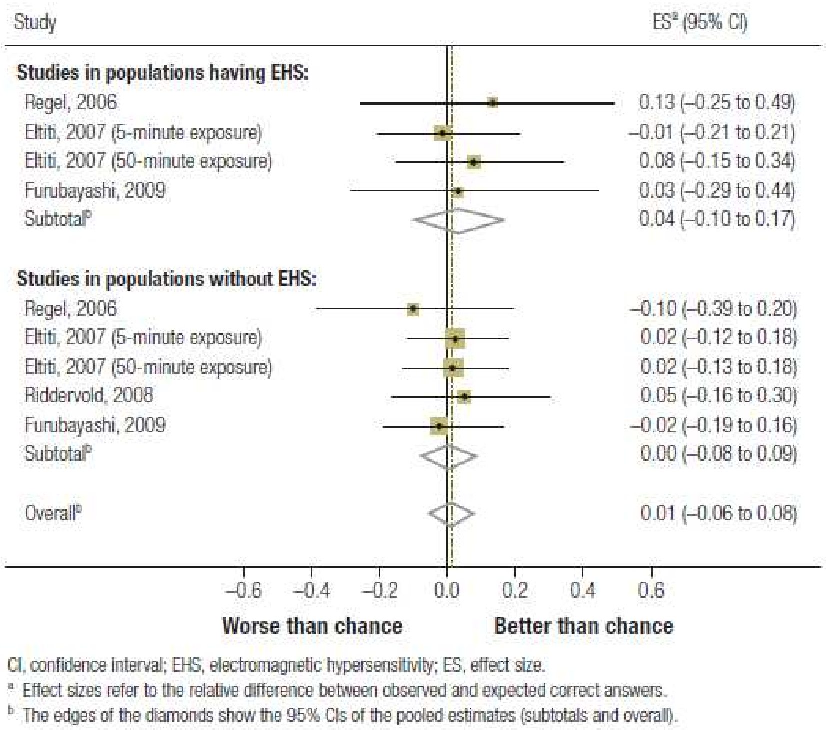
***RF-EMF and other health outcomes***

On behalf of the WHO, we performed a systematic literature review of all studies concerning exposure to mobile phone base stations and different health outcomes (Röösli et al. 2010b). This systematic literature review does not suggest that exposure to mobile phone base station causes acute effects on sleep. Additionally, no acute effects on other non-specific symptoms of ill-health can be excepted when exposed to mobile phone base station exposure under ICNIRP reference levels (Röösli et al. 2010b). Also other reviews yield the same results (Röösli 2008; Rubin et al. 2010; van Rongen et al. 2009). Van Rongen et al. (2009) investigated literature to RF-EMF exposure and possible effects on the nervous system. They concluded that a causal relation between short-term RF-EMF exposure and various symptoms has not been consistently demonstrated in provocation studies. They mentioned that psychological factors like the conscious expectation of an effect may play an important role for the development of symptoms (nocebo effect). Hence, the evidence for acute effects of RF-EMF seems to be rather small. Longitudinal effects are scarcely investigated. In the framework of the QUALIFEX project, not only RF-EMF exposure and sleep quality was observed, but also the influence of RF-EMF exposure on other non-specific symptoms of ill-health were investigated in a cohort design. In an article of Frei et al., (submitted) the results of these analyses are presented. Overall, one can say that no consistent association between longitudinal RF-EMF exposure and various symptoms of ill-health was found.

As mentioned before, long-term effects of RF-EMF exposure are sparely investigated and existing longitudinal studies, despite the QUALIFEX project, mostly address the question whether mobile phone use increases the risk of brain tumours or not. In May 2010, the long expected results of the Interphone study were published (The Interphone Study Group, 2010). The Interphone study is so far the largest multicentre case-control study which was performed between 2000 and 2004 in 13 countries and was coordinated by the WHO. Overall, the results do not indicate an increased risk for brain tumours due to mobile phone use within the first ten years of use. Results of long-term use (of more than ten years) yield a significant association between mobile phone use and brain tumours. But this result may be influence by several methodological problems.

***Electromagnetic hypersensitivity***

In our cohort, over 70% of the participants stated that RF-EMF might influence the health status in general. But only 8% considered themselves to be electromagnetic hypersensitive. In our longitudinal analysis including only EHS individuals (Article 5), we determined that EHS status in the majority of the participants was not stable over one year. This was an interesting and new finding because one would assume that symptoms due to RF-EMF do not disappear if the exposure situation does not change. In our analyses we saw that exposure situation was not associated with health status in EHS individuals. Our results are supported by findings of laboratory studies where EHS individuals were exposed to different exposure situations (Regel et al. 2006). No association between perceived exposure and the real exposure situation was found. None of the performed randomized double-blind trials could show that EHS were able to perceive the presence or even the magnitude of electromagnetic fields. Results of the specific perception studies, where study participants were exposed to mobile phone base station-like exposure, are presented in *Figure 7.3*. A meta-analysis yields no evidence that EHS individuals are able to detect the presence of electromagnetic fields in a laboratory setting. The same was concluded in a meta-analysis of Röösli (2008).




*Source: Röösli et al., 2010b*

***Figure 7.3:*** *Graphical representation of the results of field detection tests by means of randomized double-blind trials carried out in laboratory settings: results of a systematic review of studies conducted before March 2009.*

Our study indicates that the development of symptoms in EHS individuals is most likely not caused by exposure to RF-EMF. This was also observed in earlier studies where EHS individuals were exposed to mobile phone handsets, where no difference between EHS and non-EHS individuals was detected. In a study by Rubin et al. (2006), the authors tested whether EHS individuals developed more symptoms when being exposed to a pulsing mobile signal than during exposure to a sham signal or a non-pulsing signal. They found no evidence that people with self-reported sensitivity to mobile phone signals reacted with increased symptom severity. In contrary to the Rubin study, in the study of Hillert et al. (2008) headache was more commonly reported after RF exposure than sham, mainly due to an increase in the non-EHS group.

Generally, in most of the experimental human studies, results showed that mobile phone use and general RF-EMF exposure was not associated with various symptoms of ill-health (Röösli 2008) and that a nocebo effect plays an important role for the development of symptoms in EHS individuals and possibly other triggers that may cause non-specific symptoms of ill-health.

***Conclusions***

In summary, it can be stated that cross-sectional epidemiological studies do not allow firm conclusion on the influence of RF-EMF exposure on sleep quality. With our longitudinal analyses of the association between exposure and sleep quality, the evidence for the true absence of an effect of everyday RF-EMF exposure on sleep quality has increased. Also other non-specific symptoms of ill-health do not seem to be caused by short-term exposure (Röösli et al. 2010b). Data on long-term effects remain rare and the QUALIFEX study gave some first indications for the absence of an effect.

The phenomenon on EHS individuals remains unclear. There is no scientific or physiological evidence that people can perceive electromagnetic fields at low intensity levels. No consistent association between RF-EMF exposure and health problems in EHS individuals was observed in different studies. Differences in health status (independently from exposure situation) in EHS and non-EHS individuals were observed and overall, EHS individuals have a worse health status than non-EHS. Reasons for the worse health status may be complex and in medical treatment, multidisciplinary approaches are needed to treat these patients.

## 7.4 Strength and limitations of the QUALIFEX project

One main advantage of the QUALIFEX project is its longitudinal design. All previously conducted epidemiological studies on RF-EMF exposure and non-specific symptoms of ill-health including sleep quality had used a cross-sectional study design. The cohort design allows drawing more robust conclusions because selection bias is of minor concern, especially since the response rate of the follow-up survey was rather high (82%). In addition, as cohort studies measure potential causes before the outcome has occurred, the study can demonstrate that these “causes” preceded the outcome, thereby avoiding the debate as to which is cause and which is effect (Mann 2003).

Secondly, our study used the most comprehensive exposure assessment method so far. This strength is discussed in detail in Article 3 and 4. Briefly, we used several exposure surrogates to test the different hypotheses and included not only far-field sources but also close to body sources as well as all other relevant exposure sources. We also included objective operator data on mobile phone use in our analyses. To our knowledge, no previous epidemiological studies investigating symptoms in relation to EMF exposure included such objective data on mobile phone use in their analyses.

Another strength of the QUALIFEX study design is that exposure measurements were conducted in a separate study collective than the health study was performed. The full exposure prediction model was based on measurements of the exposimeter study where 166 persons carried around an exposimetric device. People of the health study did not know explicitly that the survey was about electromagnetic fields. We entitled the survey “environment and health” and asked also about other environmental factors like noise. Therewith, we tried to reduce information bias.

By using multilevel models in the nested sleep study to calculate the association between RF-EMF exposure and sleep behaviour, we had increased statistical power because we took all 14 daily actigraphic measurements of each person into account which resulted in 1484 measurements in total. We applied an autocorrelation of a one-day lag, which allowed us to additionally take the influence of the proceeding night into account.

One limitation of our study was the low response rate of 37% in the baseline survey. To evaluate the impact of a possible selection bias, we performed non-responder interviews using an additional short questionnaire. Analyses of these interviews did not show a substantial difference between responders and non-responders. To quantify the impact of possible selection bias, we calculated a selection bias factor for the cross-sectional analysis of the baseline survey. We were concerned that people attributing their sleep disturbances to RF-EMF exposure are more motivated to participate. If these people live considerably closer to a mobile phone base station than the average population, this could result in a bias, because distance is one parameter of our propagation model. Interestingly, we found indications for the opposite: Study participants were generally healthier than non-responders and the proportion of persons living close to a mobile phone base station (<50 m) was equal for both groups (Mohler et al. 2010). Thus, our selection bias modelling yielded a selection bias factor of 1.33 for living within 50 m of a mobile phone base station. If this reflects reality, estimated risk for people living within 50m from a mobile phone base station seems to be overestimated according to our selection bias analysis (bias factor > 1). For consumer products selection bias factors were <1 (0.79 for owning a mobile phone, 0.70 for owning a cordless phone, 0.95 for owning a W-LAN) indicating a “healthy communicator effect” analogue to the healthy worker effect. This means that people owning a wireless device are in general healthier than general population. Admittedly, even for the non-responder interviews the response rates were low. Among 2388 non-responders of the baseline survey, only 635 interviews could be completed.

Another limitation of our analyses was the small exposure differences between baseline and follow-up survey. Generally, exposure levels were very low and far below the ICNIRP reference levels as well as below the precautionary reference levels as defined by the ONIR for Switzerland. Therefore, we can only refer to possible low level effects. Conclusions on larger exposure changes cannot be drawn from our analyses.

The full exposure prediction model, developed and validated within the framework of QUALIFEX (Frei et al. 2009a), was based on only 166 participants and the corresponding 166 weekly measurements. Conceivably, the model is influenced by the few highly exposed participants who were intentionally recruited to gain a large range of exposure. Assigning this model to another, independent study sample may weaken the performance and there were indications that this was the case. However, in the health study we used different exposure surrogates to have information about many exposure aspects. We used objective data on mobile phone use which is a very representative exposure surrogate to assess exposure to close to body (Inyang et al. 2009; Vrijheid et al. 2009).

Although we anticipated more than 1375 participants for the health study, the statistical power of the study was adequate to detect relatively small changes in the health outcome. We performed a post-hoc power analysis which revealed that a change of 0.7 points in the daytime sleepiness score and a change of 0.5 points in the sleep disturbance score could be detected with a power of about 80%. In comparison, the sleep disturbance-scores of persons who feel disturbed by noise of their neighbours are 1.2 points higher than in persons who do not feel disturbed.

## 7.5 Public health relevance

The QUALIFEX study was embedded in the National Research Program NFP 57 which was launched in 2005 when the Federal Council approved the NFP 57. Research projects started in the beginning of 2007. This NFP was initiated because there were and still are knowledge gaps, public concerns and political debates about possible adverse health risks from electromagnetic fields. Therefore it is important to conduct adequate research in this area to be able to give reliable and consistent results to politics, public authorities and to the general population. In our longitudinal analyses, we did not find strong indication for adverse effects from RF-EMF exposure. We can assume that evidence for the absence of an effect of RF-EMF exposure on non-specific symptoms of ill-health including sleep disturbances has increased. Nevertheless, taking into account that about 90%[4] of the population owns at least one mobile phone, already a small risk would lead to many cases in our population. An expert group on electromagnetic fields recently wrote the seventh annual report from the Swedish Radiation Safety Authority (Ahlbom et al. 2010). The authors of this report conclude that a short-term risk of mobile phone use can be excluded with a high degree of certainty. If mobile phone use increased the brain tumour risk by about 40%, one would expect to observe an increase in brain tumour prevalence. So far, this is not the case (de Vocht et al. 2011; Deltour et al. 2009; Inskip et al. 2010). Nevertheless, a small risk increase of brain tumours due to mobile phone use may be still not detected yet.

In developing countries, mobile phone handsets are often the only possibility for communication. Mobile phones became also of interest for medical treatment and for drug adherence and compliance (Lester et al. 2010; Mukund Bahadur and Murray 2010). As the so called industrialised countries, it is our responsibility to investigate whether these technologies hold any risk for adverse health effects or not. One approach is to measure and monitor exposure in these countries. Recently, a study from India was published where they measured exposure to RF-EMF (COAI 2010). Exposure levels were comparable to our levels and therefore rather low.

[4] Bericht Forum Mobil, 2007. Mobilfunkmonitor Schweiz. http:www.gfsbern.ch/pub/CommuniqueD.pdf

People are still concerned about EMF. This showed the result of our analysis on how many people think that EMF can have an impact on health. In our survey, surprisingly 80% quoted that they think that EMF may provoke adverse health effects, but only 5% stated to have symptoms due to RF-EMF. As we saw in October 2010, this theme still provokes media and press interest when the results of our study were presented with a press release. Uncertainty and the lack of a biological mechanism lead to public concern and it is very important to follow research in this area and especially to monitor everyday life exposure situation in general population as well as in potentially sensitive population groups like children.

We cannot anymore imagine living without this type of technology. Adolescents and children are not anymore so concerned about possible adverse effects on health from this radiation[5]. The advantages of these devices compensate more and more the possible risks. Nowadays, mobile phones are not only used to talk, but also to communicate with the World Wide Web. Smart phones and gadgets like i-Pads have increasing sales volumes. With these new possibilities, exposure time increases rapidly and cumulative lifetime exposure dose increases for today's adolescents and children. Due to this rapid development, studies which represent current and future exposure situations are still needed.

Recently, a cohort study about mobile phone use and stress, sleep disturbances, and symptoms of depression among young adults was published (Thomee et al. 2011). In this study, the association between mobile phone use and the various health symptoms was not investigated from an exposure point of view, but from a psychological and social point of view. The risk for reporting mental health symptoms at follow-up survey was greatest among those young adults who had perceived accessibility via mobile phones to be stressful at baseline. This is an interesting study, which shows that the influence of mobile phone use on our health and life is highly complex, and even if a direct effect of the radiation could not be shown so far, the use of these devices might still influence our behaviour and mind and therefore our health related quality of life.

[5] Bericht Forum Mobil 2010. Not yet officially published

# 8 OUTLOOK

This dissertation was carried out in the framework of a national research program which included projects of different research areas. The final report of this NFP will be published in May 2011 and further steps in this research area will then be announced by the advisory board of this program. The QUALIFEX study was the only epidemiological study in this program. With the cohort design, the study contributed to increase evidence for the absence of non-specific symptoms of ill-health due to low level RF-EMF exposure.

In the future, further prospective studies on long-term effects are needed. Such a study is currently ongoing in five European countries (Denmark, Sweden, Great Britain, The Netherlands and Finland). The COSMOS (Cohort study on mobile phone use and health) study aims to carry out long-term health monitoring of a large group of people to be able to identify if there are any health issues linked to long-term mobile phone use. A big advantage of this study will be that they obtain data of mobile phone use from operators.

New technologies arise continuously (e.g. LTE – 4$^{th}$ generation of mobile communication). The consumer behaviour changes rapidly and permanently. Mobile phones are no longer exclusively used for calling reasons but increasingly for wireless internet connection. Radiofrequency identification (RFID) is also a new technology which uses radio waves to exchange data between a reader and an electronic tag which can be attached to an object. Electronic surveillance systems (EAS) in department stores are also working with radio waves. There are workers near theses EAS who claim from various health problems due to these systems and also heart pacemakers can be affected by these devices (Gimbel and Cox 2007). Due to all these new applications, exposure situation is continuously changing - for example impact of close to body sources is changing and general exposure time will probably increase. Therefore, the personal exposure situation should be monitored regularly nation widely as well as internationally. In an on-going study at the Swiss Tropical and Public Health Institute, environmental exposure levels of three different countries (Belgium, the Netherlands and Switzerland) will be measured and impact of the three different reference levels will be assessed.

Investigations in the future should focus on so called sensitive groups, like pregnant women, children and unhealthy persons, and long-term effects on health. There are studies which gave evidence that mobile phone use increases behavioral problems (Divan et al. 2010; Thomas et al. 2010). However, limitations in the study designs do not provide sufficient evidence to give a conclusive answer. Hence, good epidemiological studies in this area providing robust results are needed. In Switzerland, it is planned to conduct a similar study as the QUALIFEX study to investigate the association between children's behavior and levels of RF-EMF exposure and data on mobile phone use provided by network operators.

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# 10 CURRICULUM VITAE

| | |
|---|---|
| Name | Evelyn Mohler |
| Date of birth | 24 June 1981 |
| Nationality | Swiss |

**Education**

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|---|---|
| 1888 – 1993 | Primary school in Füllinsdorf, BL |
| 1993 – 1997 | Secondary school in Frenkendorf, BL |
| 1997 – 2000 | High school in Liestal, Matura Typ B (latin) |
| 2002 – 2007 | Swiss Federal Institute of Technology Zurich (ETHZ): Basic studies in human movement sciences, special studies in exercise physiology. Master thesis on the subject respiratory muscle training |
| Since 2007 | PhD in Epidemiology at the Institute of Social and Preventive Medicine (ISPM) in Bern and the Swiss Tropical and Public Health Institute Basel (Swiss TPH) |

**Further training**

| | |
|---|---|
| 2008 - 2011 | General principles of biostatistics, Lunteren (NL) (lecturer: K. Rothman), 5 days |
| | 4th course of the International School of Bioelectromagnetism (EBEA) "Electromagnetic fields and Epidemiology", Erice (I) (lecturers: S. Lagorio, J. Schüz et al.), 7 days |

Biostatistics I, University of Bern (lecturer: M. Zwahlen), 3 ECTS

Writing a journal article and getting it published, University of Bern (lecturers: N. Law, M. Egger), 1 ECTS

Multilevel analysis, University of Basel (lecturers: M. Röösli), 1 ECTS

SSPH+ Summer School: Health care management, University of Lugano (lecturer: K. White), 1 ECTS

Mixed Methods Research and Evaluation, University of Basel (lecturer: M. Bergman), 1 ECTS

Observational epidemiological studies: advanced methods for design and analysis, University of Basel (lecturers: J. Schwartz, M. Röösli), 2 ECTS

Media Training, University of Bern (lecturer: C. McIntryre, S. Suggs) 0.5 ECTS

Conduct a systematic review, University of Bern (lecturer: M. Egger), 0.75 ECTS

**Working experience**

| | |
|---|---|
| 2004 - 2005 | Assistant at the Laboratory of Biomechanics, ETH Zürich |
| 2006 | Internship at the Swiss Paraplegic Centre, Sports medicine, Nottwil |
| 2006 - 2007 | Assistant at the Institute of Physiology, University of Zurich |
| Since 2010 | Scientific collaborator at the Federal Office of Public Health, Division radiological protection, Bern |

**List of Publications**

Röösli M, Frei P, Mohler E, Braun-Fahrländer C, Bürgi A, Fröhlich J, Neubauer G, Theis G, Egger M. Statistical analysis of personal radiofrequency electromagnetic field measurements with nondetects. Bioelectromagnetics. 2008;29(6):471-8.

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Röösli M, Frei P, Bolte J, Neubauer G, Cardis E, Feychting M, Gajsek P, Heinrich S, Joseph W, Mann S, Martens L, Mohler E, Parslow RC, Poulsen AH, Radon K, Schüz J, Thuroczy G, Viel JF, Vrijheid M. Conduct of a personal radiofrequency electromagnetic field measurement study: proposed study protocol. Environ Health. 2010;9:23.

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Frei, P., Mohler, E., Neubauer, G., Fröhlich, J., Braun-Fahrländer, C., Röösli, M., QUALIFEX-team. Cohort study on the effects of radio frequency electromagnetic field exposure in everyday life on non-specific symptoms of ill health and tinnitus. submitted.

Lauer, O., Neubauer, G., Röösli, M., Riederer, M., Mohler, E., Frei, P., Fröhlich, J. Reliable assessment of the measurement accuracy of band-selective personal exposure meters: an example study. In the review process.

Mohler, E., Frei, P., Braun-Fahrländer, C., Fröhlich, J., Röösli, M., (2012) Exposure to Radiofrequency Electromagnetic Fields and Sleep Quality: A Prospective Cohort Study. PLoS ONE 7(5): e37455. doi:10.1371/journal.pone.0037455

**Conference Contributions**

02.10.2008 E. Mohler: Individual exposure to radio frequency electromagnetic fields: preliminary results from QUALIFEX. Jahrestagung GHUP, Graz, Österreich.

19.06.2009 E. Mohler: Effects of RF-EMF exposure on sleep quality: a cross-sectional study. Annual Meeting of the Bioelectromagnetics Society (BEMS), 14-19.06.2009. Davos.

27.08.2009 E. Mohler: Effects of RF-EMF exposure on sleep quality: a cross-sectional study. Annual conference of the International Society for Environmental Epidemiology (ISEE), Dublin.

30.08.2010 E. Mohler: Effects of RF-EMF exposure on sleep behaviour: a longitudinal analysis. Annual conference of the International Society for Environmental Epidemiology (ISEE), Seoul.

22.02.2011 E. Mohler: Does radiofrequency electromagnetic field exposure influence sleep behaviour? 10$^{th}$ International Conference of the European Bioelectromagnetics Association (EBEA), Rom.

**Teaching activities**

26.10.2009 Kurs von ASEB: Nichtionisierende Strahlung (Elektrosmog): Fakten, Risiken und Rechtsgrundlagen - hoch und niederfrequente Strahlung: Gesundheitliche Auswirkungen von elektromagnetischen Feldern, Liebefeld

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| 28.10.2010 | Kurs von ASEB: Nichtionisierende Strahlung (Elektrosmog): Fakten, Risiken und Rechtsgrundlagen - hoch und niederfrequente Strahlung: Gesundheitliche Auswirkungen von elektromagnetischen Feldern, Liebefeld |