INVESTIGATION OF EXPOSURES AND HEALTH EFFECTS FROM MOBILE PHONES AND OTHER SOURCES OF RADIO-FREQUENCY RADIATION

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Abstract

Over the last two decades, the number of mobile phone (MP) users has increased dramatically. The radiofrequency-electromagnetic field (RF-EMF) exposure due to the use of MP is a primary source of man-made RF-EMF exposure in general populations. There have been concerns regarding long-term RF-EMF exposures to human populations and potential health consequences. The International Agency for Research on Cancer (IARC) in 2011 categorised RF-EMF exposure as a possible human carcinogen. Furthermore, there has been an ongoing concern that the use of MP and cordless phone (CP) by children may affect their cognitive development. The World Health Organization in 2010 emphasised the need for quantification of personal exposures from different RF-EMF sources, and performance of more research in the domain of children's RF-EMF exposure and psychological outcomes. The primary aim of this PhD thesis was to increase understanding of personal and environmental RF-EMF exposures, and potential cognitive health effects in a sample of children due to the exposures from mobile and cordless phones.

This thesis: i) reviewed instruments to assess and measure personal and environmental RFEMF exposures, ii) measured personal RF-EMF exposure at 900 MHz frequency across 34 microenvironments in Australia and Belgium using a novel personal distributed exposimeter, iii) measured personal RF-EMF exposure (88 MHz-5.8 GHz) across 38 microenvironments in Australia and Belgium with two on-body calibrated exposimeters, iv) assessed environmental and personal RF-EMF exposures in kindergarten children, and v) assessed possible longitudinal associations between the use of MPs and CPs in a cohort of primary school children (n=412) and effects on their cognitive function.

Chapter 2 presents various state-of the-art tools that have been or could be used in RF-EMF exposure assessment for epidemiological research. It concludes that assessment of RF-EMF exposures could be improved by using tools providing quantitative measures of RF-EMF exposure.

Chapter 3 and 4 present data on microenvironmental personal RF-EMF exposures in Melbourne, Australia and Ghent, Belgium. The three highest personal RF-EMF exposures (900 MHz downlink) were characterised for: city centre, bus, and railway station [Australia]; and bicycle (urban), tram station, and city centre, [Belgium]. Similarly, the three highest personal RF-EMF (88 MHz-5.8 GHz) exposures were characterised for: city centre, residential outdoor (urban), and a park [Australia]; and a tram station, city centre, and a park [Belgium].

The largest source of RF-EMF exposure to kindergarten children was attributed to mobile phone base station(s), particularly 900 MHz downlink (chapter 5). The contribution of Wi-Fi was minimal. Furthermore, environmental RF-EMF exposure levels at kindergartens located <300 m away from the nearest base station were higher compared with those located >300 m.

Findings in chapter 6 showed that a higher proportion of children used CPs compared to MPs. The overall results indicated that there was limited evidence that changes in the use of MPs/CPs in primary school children were associated with changes in cognitive function.

For the first time, the feasibility of measuring personal exposures with on-body calibrated personal distributed exposimeters and a pair of ExpoM-RFs™ was demonstrated.

Furthermore, it was demonstrated that the concurrent use of two on-body calibrated ExpoM-RFs™ measured RF-EMF exposures more accurately compared to those provided with a single non-on-body calibrated exposimeter. This work provides a proof-of-concept to carry out RF-EMF exposure assessment in pre-school children for future RF-EMF epidemiological studies.

I recommend that RF-EMF exposure assessments should be continued in future studies in order to inform the general public regarding existing RF-EMF exposure levels, monitor changes in RF-EMF exposure levels over time, and account for new exposure types and frequency bands, as well as cumulative exposure. In particular, further research in the domain of young children's exposure to RF-EMF sources (e.g. smart mobile phones, tablets/iPads®, etc.) and long-term potential health or cognitive effects should get more attention. Assessment of RF-EMF exposures and potential population health effects will have implications for informing the general public about the exposure scenarios in relation to their health and well-being, and formulating evidence-based RF-EMF policies.

Declaration

I hereby declare that this thesis contains no material which has been accepted for the award of any other degree or diploma, except where due reference is made in the text of the thesis. To the best of my knowledge, this thesis contains no material previously published or written by another person except where due reference is made in the text of the thesis.

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General Declaration

In accordance with Monash University Doctorate Regulation 17.2 Doctor of Philosophy and Research Master's regulations, the following declarations are made:

I hereby declare that this thesis contains no material which has been accepted for the award of any other degree or diploma at any university or equivalent institution and that, to the best of my knowledge and belief, this thesis contains no material previously published or written by another person, except where due reference is made in the text of the thesis. This thesis includes one review and three original papers published in peer reviewed journals and one unpublished manuscript. The core theme of the thesis is '*Investigation of exposures and health effects from mobile phones and other sources of radio-frequency radiation*'. The ideas, development and writing up of all the papers in the thesis were the principal responsibility of myself, the candidate, working within the School of Public Health and Preventive Medicine under the supervision of Doctor Geza Benke, Doctor Mary Redmayne and Professor Michael J Abramson. The inclusion of co-authors reflects the fact that the work came from active collaboration between researchers and acknowledges input into team-based research.

In the case of chapters 2 to 6, my contribution to the work involved as the following:

Thesis chapters	Publication titles	Publication status	Nature and extent of candidate's contribution
2	Instruments to assess and measure personal and environmental radiofrequency-electromagnetic field exposures	Published	Literature search, review, manuscript development and preparation
3	Measuring personal exposure from 900 MHz mobile phone base stations in Australia and Belgium using a novel personal distributed exposimeter	Published	Study design, data collection, data analysis, manuscript development and preparation
4	Assessment of personal exposure from radiofrequency-electromagnetic fields in Australia and Belgium using on-body calibrated exposimeters	Published	Study design, data collection, data analysis, manuscript development and preparation
5	Radiofrequency-electromagnetic field exposures in kindergarten children	Published	Study design, ethics application, data collection, data analysis, manuscript development and preparation
6	Use of mobile and cordless phones and change in cognitive function: a prospective cohort analysis of Australian primary school children	Accepted	Data analysis, manuscript development and preparation

I have renumbered sections of the published and submitted papers in order to create a consistent presentation within the thesis.

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List of Abbreviations

1G	First Generation wireless telephone (mobile phone) technology
2G	Second Generation wireless telephone (mobile phone) technology
3G	Third Generation wireless telephone (mobile phone) technology
4G	Fourth Generation wireless telephone (mobile phone) technology
ABCD	Amsterdam Born Children and their Development
AM	Amplitude Modulation
ARPANSA	Australian Radiation Protection and Nuclear Safety Agency
CP	Cordless Phone
DECT	Digital Enhanced Cordless Telecommunications
DL	Downlink
DVB-T	Digital Video Broadcasting-Terrestrial
EHS	Electro-hypersensitivity
ExPOSURE	Examination of Psychological Outcomes in Students Using Radiofrequency dEvices
FM	Frequency Modulation
GHz	Giga Hertz
GSM	Global System for Mobile communication
HMP	Hardware Modified Phone
IARC	International Agency for Research on Cancer
ICNIRP	International Commission on Non-Ionizing Radiation Protection
INTERPHONE	International Case Control Study of Tumours of the Brain and Salivary Glands
ISM	Industrial, Scientific and Medical

ITU	International Telecommunication Union
LOD	Lower Detection Limit
LTE	Long-Term Evolution
MHz	Mega Hertz
MoRPhEUS	Mobile Radiofrequency Phone Exposed Users' study
MP	Mobile Phone
RADAR	RAdio Detection And Ranging
RF-EMF	Radiofrequency-Electromagnetic Field
RF-EMR	Radiofrequency-Electromagnetic Radiation
PDE	Personal Distributed Exposimeter
SAR	Specific Absorption Rate
SD	Standard Deviation
SES	Socio-Economic Status
SEIFA	Socio-Economic Indexes For Areas
SMS	Short Messaging Service
SMP	Software Modified Phone
UL	Uplink
WHO	World Health Organisation
WLAN	Wireless Local Area Network
Wi-Fi	Wireless Fidelity
WiMax	Worldwide Interoperability for Microwave Access

List of Appendices

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Chapter 1. Introduction

1.1. Mobile Telephony – History of Evolution

Since 1973 when the world's first mobile phone (MP) call was placed in the USA (1), MPs have been one of the most popular personal devices for communication worldwide. MP technology and its capabilities have evolved tremendously – from the first generation (1G) to the current fourth generation (4G) technology. In parallel to this, the number of MP users also increased dramatically particularly over the last decade. For instance, the number of MP subscriptions in Australia was reported to be nearly 21.18 million (penetration rate of 99.6%) in 2007 and the number climbed to more than 31 million in 2015 (penetration rate of 138%) (2). According to the International Telecommunication Union (ITU), the global population subscribing to MPs has reached more than seven billion in 2016 (3).

The use of MP communication is reliant upon the operation of networks of radiofrequency-electromagnetic fields (RF-EMFs). In the literature, RF-EMF and RF-EMR (radiofrequency-electromagnetic radiation) have been used interchangeably. By definition, RF-EMFs fall within the non-ionizing part of the electromagnetic spectrum with a frequency range of 3 kHz–300 GHz (4). This is a wide frequency spectrum and MP technology has used only a part of the frequency range, depending on the generation of MP technology. The evolution of MP technology has involved the increased amount of digital data it sends and receives via RF-EMF signals. Subsequently, this has also allowed the enhancement of the functionalities of MPs, including the ability to offer data/online-multimedia services.

The early 1G technology characterized an analogue version of MPs mainly used for voice transmission operating at 900 MHz (5). The first official 1G MP call in Australia was made in 1987 (6). The second generation (2G) technology, commercially launched in Global System for Mobile communication (GSM) standard, characterised digital technology and was mainly used for voice communication and short text messaging services (SMS). The GSM network in Australia was officially switched on in 1993 (7), which has been operating at 900 MHz and 1800 MHz. The third generation (3G) MP technology that operates at 2100 MHz superseded the 2G. The technology provides improved services such as wide area wireless voice calls and SMS, video calls, wireless data and multimedia. The 3G digital MP system is able to operate at multiple frequencies of 800/900 MHz, 1.7-1.9 GHz, and 2.5-2.69 GHz (8). In Australia, the 3G technology rolled out from 2005 (6) and operates at 850 MHz, 900 MHz, and 2.1 GHz (9). The application of the 3G network has become popular worldwide, particularly due to the notable development of smartphones such as the iPhone, and the Android-based MPs. The fourth generation (4G) MP system is the latest MP technology in use that provides ultra-broadband Internet service in addition to what 3G has to offer. The 4G technology in Australia commenced in 2014 (6), and it utilises the frequency bands of 700 MHz, 850 MHz, 900 MHz, 1.8 GHz, 2.1 GHz, 2.3 GHz, and 2.6 GHz (9).

In nearly all countries throughout the world, MP networks are constituted of strategically located base stations so as to provide voice calls, SMS or other online-multimedia/data services across wide geographical areas. The MP network is characterised by two types of RF-EMF signals, which are called downlink (DL) and uplink (UP). The DL signals are emitted from base stations and received by MPs, whereas the UP signals are emitted from MPs and received by the base stations. The DL and UL signals have slightly different frequencies depending on network MP allocations.

1.2. Telecommunication and Broadcasting Systems

In addition to MPs, there are a number of other telecommunication and broadcasting technologies around us – cordless phones, radios and televisions, Wi-Fi, general packet radio service, wireless garage door openers, anti-shoplifting alarms, radio-frequency identification devices, to name a few.

Table 1 below lists some of these technologies operating in different frequency bands. The International Telecommunication Union globally allocates portions of the radio spectrum. Their subsequent local allocations may vary across different countries.

Table 1. Frequency bands of some of the key telecommunication and broadcasting systems

Telecommunication and Broadcasting systems	Frequencies
AM radio	300 kHz–3000 MHz (10, 11)
FM radio	88–108 MHz (10, 11)
Analogue TV Broadcasting	174–223 MHz (10, 11)
Terrestrial Trunked Radio	380-400 MHz (10, 11)
Digital Video Broadcasting	470–830 MHz (10, 11)
Digital Enhanced Cordless Telecommunications (DECT)/Cordless Phone	30–40 MHz (12), 900 MHz (13), 1.88–1.9 GHz (10, 11), 2.4 GHz & 5.8 GHz (12)
Wireless Local Area Network (WLAN)/Wi–Fi	2.4–2.5 GHz (10, 11), 5.15–5.35 GHz, 5.725–5.85 GHz (14)

The discussion in this thesis is limited to the RF-EMF exposures from MPs and the other telecommunication and broadcasting technologies listed in table 1, operating in the frequency range between 88 MHz and 5.8 GHz.

1.3. MP and Cordless Phones (CP) Use in Children

Children have been increasingly using mobile and cordless phones worldwide (15-21). This is suggested by the trends of MP use in many countries. The Mobile Radiofrequency Phone Exposed Users' Study (MoRPhEUS) reported that the proportion of MP ownership amongst Australian children (median age 13 years) increased from 75% in 2005/2006 to 86% in 2007 (15). In Korea, the ownership of MPs in children (mean age 9 years) increased from nearly 23% to 65.5% during 2008–2010 (22). In the US, the use of MPs in children (aged 8 and under) climbed from 38% to 72% during 2011–2013 (23). A recent report found that on average 69% of children (aged 9–16 years) in Belgium, Denmark, Ireland, Italy, Japan, Portugal, Romania and the United Kingdom used MP in 2013 (24).

The use of CPs, along with MPs, has been popular among children. It has been found in some studies that the prevalence of CP use in children has been even higher than that of MP use. The Examination of Psychological Outcomes in Students Using Radiofrequency dEvices (ExPOSURE) study reported that 80% of children (mean age 10 years) used CP during 2011–2012 (18). Whereas, the same study reported that the use or ownership of MP was 31% (18) during the same period. In New Zealand, approximately 90% of students (median age 13 years) used MP and CP by 2009 (16). The prevalence of CP use amongst the 5–6 years old children in the Netherlands was around 84% during 2008–2010 (21). Whereas 48% of the children used/owned a MP (21).

In addition to voice calls, with the introduction of smart phones, children use MPs for listening to music, watching videos, surfing Internet and connecting to social networks (Facebook, Twitter, Instagram, etc.), and so on (24, 25).

1.4. RF-EMF Exposures

Exposure to radiofrequency-electromagnetic fields (RF-EMFs) is omnipresent. However the RF-EMF exposure to humans as a consequence of naturally occurring sources, such as the sun, earth and ionosphere, is insignificant compared to that from man-made sources, particularly telecommunication and broadcasting technologies (26, 27). The benefits offered by these technologies, including MPs, to society, therefore come at the cost of associated RF-EMF exposures to human populations.

The RF-EMFs from radio antennas constitute the primary source of RF-EMF exposures to humans. Depending on the distance of the RF-EMF emitting antennas from the human body, RF-EMF exposures have been categorised into near-field and far-field exposures (28). The sources of near-field exposure are mobile phone, cordless phones, laptops, tablets and iPads™. On the other hand, mobile and cordless phone base stations, Wi-Fi hotspots/routers, and radio/TV broadcast stations comprise the sources of far-field exposures.

Technically, far-field exposure commences at a distance of $2D^2/\lambda$, where D is the largest dimension of the RF-EMF emitting antenna, and λ is the RF-EMF wavelength in air (29). The RF-EMF exposure rapidly decreases with increasing the distance from the RF-EMF antenna. Therefore, near-field exposure contributes the most to the total human RF-EMF exposures. Far-field exposure levels are generally lower compared to near-field exposures, but involve involuntary exposure of the whole body. Compared to far-field exposures, near-field exposures are generally higher and involve voluntary exposure of a localised body or body parts (e.g. human head while using MP) (30).

Human exposure to the near-field RF-EMF sources is very difficult to estimate, particularly for epidemiological studies. Specific absorption rate (SAR) is the quantitative measure of the near-field RF-EMF exposure, which is defined as the energy absorption rate per unit mass of the biological tissue (watts/kg) [SAR = $\sigma \times E^2/\rho$, where σ, E, and ρ are the tissue conductivity (S/m), the induced electric field or intensity (V/m) in the tissue of interest, and the tissue mass density (Kg/m^3), respectively]. These measurements cannot be performed in a living head, are therefore performed with human phantoms in sophisticated laboratories (31). Therefore, surrogate exposure measures are commonly used in estimating near-field exposures in epidemiological studies. The far-field (personal or environmental) RF-EMF exposures can be measured with different types of "exposimeters". These instruments provide an objective measure of electric field intensity (volt/m) or power density (watt/m^2) values.

Internationally, the guidelines of the International Commission on Non-Ionizing Radiation Protection (ICNIRP) have been widely followed in order to limit RF-EMF exposures to the general public and occupational populations. The RF-EMF exposure limits in the ICNIRP standards have been provided in terms of basic restrictions and reference levels to protect humans against established health effects (mainly acute tissue heating) (32). The basic restrictions include safety factors directly related to known health effects (i.e. thermal effects), and are expressed in terms of electric field strength, SAR, and power density. Whereas, the reference levels are recommended for practical purposes to ensure compliance with basic restrictions in real-life situations. The reference levels are expressed in terms of easily measurable or calculable limits of electric/magnetic field strengths, power density or body current. In Australia, the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) follows similar RF-EMF exposure standards (33).

1.5. Potential Health Effects of RF-EMF exposures

With the expansion of telecommunication technology worldwide, it has raised public health concerns regarding potential health effects as a consequence of RF-EMF exposures. The Eurobarometer survey performed in 2010 found that 46% of people in the 27 European countries were fairly or very concerned about potential health risks of RF-EMF (34). Limited RF-EMF epidemiological research indicates that the potential health effects related to RF-EMF exposure appear to be related to the long-term use of MP/CP and development of head and neck tumours, or those related to children's use of MP and CP and their psychological well-being.

1.5.1. MP/CP Exposure and Head and Neck Tumours

There has been inconsistent epidemiological evidence suggesting that excessive mobile phone use may be a risk factor for brain tumours. Case-control studies performed by Hardell's group in Sweden (35-37) reported that long term exposure to analogue mobile phones was found to be associated with the occurrence of brain/head and neck tumours (e.g. acoustic neuroma and low-grade astrocytoma). A case-control study including five North European countries (1,522 glioma cases and 3,301 controls) also suggested an association between the long term (>10 years) ipsilateral use of MP and occurrence of glioma (38). The International Case Control Study of Tumours of the Brain and Salivary Glands (INTERPHONE), the case–control study including 13 countries (2765 glioma cases, 2425 meningioma cases and 7658 controls), suggested that a long-term excessive use of MP (≥1640 hours) may be associated with an increased risk of developing glioma alone (but not for other tumours) (39-41). The French CERENAT case-control study (253 glioma, 194 meningioma cases and 892 controls) indicated a positive association between a long-term use of MP and occurrence of gliomas and meningioma (42). However, other case-control and cohort studies provide no such evidence (43, 44). Based on some of these results, the International Agency for Research on Cancer (IARC) in 2011 categorised RF-EMF exposure as a possible human carcinogen (45).

1.5.2. RF-EMF Exposure and Cognitive Effects in Children

There are conflicting findings regarding whether children are more sensitive or not than adults to RF-EMF exposures (46-48). Some countries therefore follow the 'precautionary approach', especially to limit the exposures to children (17). There have been concerns regarding whether RF-EMF exposures associated with the use of mobile and cordless phones have psychological effects on the developing brains of children (15, 18, 20, 21, 49, 50). It has been assumed that children could be more susceptible to the potential health effects related to RF-EMF exposures due to higher lifetime cumulative RF-EMF exposures. The use of MPs and CPs in children has been linked with negative outcomes in cognitive functioning (15, 51) including memory performance (20).

Mobile phone voice calls constitute the largest source of RF-EMR exposure, especially to the brain (30). Therefore, this particular exposure is relevant in view of its potential impact on children's cognition due to their increasing use of MPs. In response to this, the World Health Organization (WHO) recommended performing prospective cohort studies of children with outcomes such as behavioural and neurological disorders (50). It is not yet understood how MP/CP RF-EMF exposure affects human behaviour and neurological disorders, including cognitive function. One of the hypotheses could be related to the potential role of temperature elevation (i.e. thermal effects) of RF-EMF exposure (1). Furthermore, RF-EMF may change electrical field potentials generated by cells, and excitability of neurons resulting in polarised membranes (2).

Human cognitive tasks, in particular learning and memory processes, are mainly associated with the hippocampus, which is anatomically situated within the temporal region of the brain. If RF-EMF exposure could potentially affect the learning and memory in one way or another, this particular region should be influenced by the absorption of RF-EMF. Interestingly, it has been demonstrated that the temporal lobes of the brain is the area where more than 50% of the MP associated RF-EMF exposure is absorbed (3). Therefore, it could be hypothesised that RF-EMF absorption which takes place in temporal lobe of the brain due to MP usage may influence human cognitive function. However, it is still unclear exactly how RF-EMF exposure to the hippocampus could affect cognitive tasks such as those related to learning and memory.

There are limited community-based epidemiological studies involving children that assessed effects of MP and/or CP exposure on cognitive function (15, 18, 20, 21, 51). The findings of these studies are inconclusive. The MoRPhEUS study, assessing cross-sectional data on MP use and cognitive effects in secondary school children, found MP use was associated with faster and less accurate response to higher level cognitive tasks (51). Nevertheless, longitudinal analysis showed little effect of MP use on the children's cognition (15). A recent Swiss study involving adolescents found a negative association between MP and CP use with figural memory (20). The Amsterdam Born Children and their Development (ABCD) study showed inconsistent associations between MP and CP use and cognitive function (21). Furthermore, the cross-sectional data of the ExPOSURE study suggested that there was little evidence for an association between the use of MPs and CPs and cognitive effects in primary school children in Australia (18). However, these studies used different methodologies to assess cognitive function and more research is needed to further explore possible associations.

1.5.3. Other Potential Health Effects of RF-EMF Exposure

The RF-EMF exposures from mobile phone base stations are far less than those from near-field devices such as from MP or CP (30). In view of the general public's concerns about potential health and well-being effects of low-level chronic RF-EMF exposures from mobile phone base stations, some epidemiological studies have investigated potential health effects of exposures from mobile phone base stations with mixed findings (55-61).

The cross-sectional studies from Austria and Spain (59, 60) found that self-reported symptoms – such as headache, difficulty in or lack of concentration, fatigue, irritability, lack of appetite, depression and sleep problems – were associated with RF-EMF exposures from mobile phone base stations. Contrary to these findings, a cross-sectional study from Germany (61) showed that the base station RF-EMFs were not associated with self-reported adverse health effects such as headaches, health complaints, mental and physical health, and sleep disturbances. Similarly, another German cross-sectional study found no significant association between mobile phone base station RF-EMF exposure and chronic or acute health symptoms such as headache, tinnitus, tachycardia, concentration problems, fatigue and sleeping disorders (57). The average mobile phone base station exposure levels measured in these studies were comparable and far below the ICNIRP reference level (57, 59-61). However, the studies slightly differ in the way how RF-EMF exposures and health symptoms were assessed (e.g. questionnaire and tests administered for heath/mental wellbeing). Therefore, it is difficult to make a direct comparison of these findings and draw a conclusion.

Electrohypersensitivity (EHS) has been reported in many countries by patients who claim specific symptoms are linked with RF-EMF exposures (63, 64). The most commonly reported symptoms of EHS are redness, tingling, and burning sensations (dermatological), fatigue, tiredness, concentration difficulties, dizziness, nausea, heart palpitation, and digestive disturbances (neurasthenic and vegetative) (64). However these symptoms are not clearly linked with any recognised syndrome. The WHO suggests that current scientific evidence does not support any causal relationship between RF-EMF exposure and EHS (64). A recent double-blind randomised controlled trial was performed in the Netherlands to assess effects of personalised exposure on self-rated EHS on 42 individuals (mean age 55 years) at baseline and follow-up (65). The study found that no participant was able to find RF-EMF exposure better than chance. Also, the study did not find any statistically significant differences between the self-reported level of EHS at follow-up and that at baseline, but at follow-up the participants reported reduced certainty while reacting within minutes to RF-EMF exposure and significantly fewer symptoms than those at baseline (65).

1.6. Rationale for the PhD thesis

It is widely recognised that the key limitation of RF-EMF related epidemiological studies is reliable RF-EMF exposure assessment. It is recognized that inappropriate/crude methods of exposure assessment could result in exposure misclassification and biased findings (66-68). In view of improving the exposure assessment approaches for RF-EMF epidemiological studies, the World Health Organization (WHO) in 2010 underlined the need for quantification of personal exposures from different RF-EMF sources and performance of rigorous epidemiological studies (50). The WHO also recommended that further research in the area of children's behavioural and neurological outcomes associated with RF-EMF exposures should also be performed (50).

Several European countries have conducted the research in the area of environmental and personal RF-EMF exposure assessments (69-77). However in Australia, RF-EMF exposure information was largely unknown despite the increasing deployment of MP technology and very high market penetration (78). Only limited information on environmental exposure from MP base stations, particularly at locations close to the base stations in Australia, was available (79-81). Therefore, there was a need to evaluate environmental and personal RF-EMF exposures in Australia. In particular, there were little data available internationally describing RF-EMF exposures to young children (e.g. kindergarten and school children) (75, 82-84). For instance, there has been a concern in Australia, regarding the RF-EMF exposures near schools (84-86).

Though research in RF-EMF exposure assessment is continuing, innovative approaches to exposure assessment are desperately needed in this field of research. For instance, the assessment of far-field personal RF-EMF exposures in human environments so far have been performed with a body-worn exposimeter, despite the fact that this method gives uncertain measurements, mainly related to body-shielding (87-90). It has been suggested that the use of a pair of exposimeters, each placed on different body locations, would minimize such uncertainty (90, 91). Such a placement of the on-body calibrated exposimeters has been shown to reduce the measurement uncertainty (92). Therefore, testing and validation of new exposure assessment tools and approaches, including this approach, is necessary to improve the knowledge RF-EMF exposure assessment.

Due to the different measurement protocols followed by different study groups, the comparison of RF-EMF measurements across the different countries has been challenging. Therefore, exposure measurements in a European country and other regions of the world (e.g. Australia), employing similar study tools/methods, would allow a direct comparison of RF-EMF exposure levels.

1.7. PhD thesis aims and objectives

The overarching aim of this PhD thesis is to increase understanding of personal and environmental RF-EMF exposures, and reliable assessment of population health effects associated with RF-EMF exposures.

The specific objectives were to:

i) conduct a literature review of the RF-EMF exposure assessment tools that can be used in epidemiological studies

ii) assess personal RF-EMF exposure across various microenvironments in Melbourne (Australia) and in/around Ghent (Belgium)

iii) evaluate RF-EMF exposures in kindergarten children

iv) examine the longitudinal association between the use of MP and CP in a cohort of primary school children and potential effects on their cognitive development

This thesis addresses the above mentioned objectives, which are discussed in different chapters. Firstly, chapter 1 reviews currently available state-of-the-art tools for RF-EMF exposure from different sources. Secondly, based on this review, chapters 3, 4 and 5 (RF-EMF exposure measurement studies) employed one or more of these tools in different contexts to perform environmental and personal RF-EMF measurements. Finally, chapter 6 (health outcome study) presents the findings on the assessment of children’s cognitive health outcomes in relation to their MP or CP usage.

Chapter 2. Instruments to assess and measure personal and environmental RF-EMF Exposures

Overview

Radiofrequency-electromagnetic field (RF-EMF) exposure of human populations is increasing due to the widespread use of mobile phones and other telecommunication and broadcasting technologies. Therefore, objective assessment of environmental and personal RF-EMF exposures is important to characterise these exposures in view of current and future epidemiological studies.

This chapter critically examines and identifies the currently available tools for RF-EMF exposure assessment in epidemiological studies, discusses their strengths and limitations, and provides relevant recommendations for future development.

Declaration for Thesis Chapter 2

Manuscript: **Bhatt CR,** Redmayne M, Abramson MJ, Benke G. Instruments to assess and measure personal and environmental radiofrequency-electromagnetic field exposures. *Australasian Physical & Engineering Sciences in Medicine* 2016, 39: 29–42

Declaration by candidate

In the case of Chapter 2, the nature and extent of my contribution to the work was the following:

Nature of contribution	**Extent of contribution (%)**
Literature search, manuscript preparation and editing, and revision of submitted manuscript	80%

The following co-authors contributed to the work. Where co-authors are students at Monash University, the extent of their contribution in percentage terms is stated:

Names	**Nature of contribution**
Mary Redmayne	Manuscript editing, revision of submitted manuscript and supervision
Michael J Abramson	Manuscript editing, revision of submitted manuscript and supervision
Geza Benke	Manuscript editing, revision of submitted manuscript and supervision

The undersigned hereby certify that the above declaration correctly reflects the nature and extent of the candidate's and co-authors' contribution to this work.

Candidate's Signature	[redacted]	Date 28/04/2017

Main Supervisor's Signature	[redacted]	Date 28/04/2017

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REVIEW

Instruments to assess and measure personal and environmental radiofrequency-electromagnetic field exposures

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Abstract Radiofrequency-electromagnetic field (RF-EMF) exposure of human populations is increasing due to the widespread use of mobile phones and other telecommunication and broadcasting technologies. There are ongoing concerns about potential short- and long-term public health consequences from RF-EMF exposures. To elucidate the RF-EMF exposure-effect relationships, an objective evaluation of the exposures with robust assessment tools is necessary. This review discusses and compares currently available RF-EMF exposure assessment instruments, which can be used in human epidemiological studies. Quantitative assessment instruments are either mobile phone-based (apps/software-modified and hardware-modified) or exposimeters. Each of these tool has its usefulness and limitations. Our review suggests that assessment of RF-EMF exposures can be improved by using these tools compared to the proxy measures of exposure (e.g. questionnaires and billing records). This in turn, could be used to help increase knowledge about RF-EMF exposure induced health effects in human populations.

Keywords Exposimeters · Mobile phone exposures · Radiofrequency-electromagnetic exposures · Radiofrequency-electromagnetic exposure assessment · Radiofrequency-electromagnetic exposures tools

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Introduction

Exposure to radiofrequency-electromagnetic fields (RF-EMFs) is universal. RF-EMFs either come from naturally occurring sources like the sun, earth and ionosphere, or from anthropogenic sources such as telecommunication and broadcast systems [1]. Human exposure from naturally occurring sources is negligible compared to that from the anthropogenic sources [1, 2]. RF-EMF radiation falls within the non-ionizing part of electromagnetic spectrum with a frequency range of 3 kHz–300 GHz [3]. However the fact that RF-EMF is non-ionising does not necessarily mean that it may be completely harmless to humans as its interaction with living systems has been reported to induce numerous biological effects [4]. International guidelines or standards, which are based on established adverse health effects (e.g. tissue heating), have been widely used to limit RF-EMF exposure to general public and occupational populations [1, 5].

In recent years, we have increasingly adopted radiofrequency technologies. The examples and the frequency ranges associated with some of the common technologies in use are: AM radio (300 kHz–3000 MHz), FM radio (88–108 MHz), analogue TV and Digital Video Broadcasting (174–223 MHz and 470–830 MHz), Terrestrial Trunked Radio (380–400 MHz), Digital Enhanced Cordless Telecommunications (DECT, 1.88–1.9 GHz), Wireless Local Area Network (WLAN, also called Wi-Fi) and Bluetooth (2.4–2.5 GHz), mobile phone downlink and uplink (900 MHz–2.17 GHz) respectively [6, 7]. Cordless phone technology further makes the use of 30–40 MHz [8], 900 MHz [9], 2.4 GHz, and 5.8 GHz frequencies [8]. Similarly, WLAN technology in recent years also utilizes the higher frequency bands of 5.15–5.35 GHz and 5.725–5.85 GHz [10]. However, these frequency ranges may vary by country depending on how frequency spectra are allocated. There are also other technologies operating within the RF-EMF spectrum: radio detection and ranging (RADAR), smart meters, baby monitors, general packet radio service, wireless garage door openers, anti-shoplifting alarms, radio-frequency identification devices, near field communication devices, etc.

The number of mobile phone subscriptions worldwide is about to reach 7 billion, and those subscribing to an Internet service are estimated to be as many as 3 billion by the end of 2014 [11]. The use of cordless phones is also a common phenomenon worldwide [12–15], which is popular with landline phone installations. Not only do these facts and figures show that telecommunication has greatly expanded, but the situation has also raised growing health concerns regarding the increased potential exposures to RF-EMF associated with them. A primary concern is the development of tumours of the brain, acoustic nerve and parotid glands following a long term exposure to mobile phones, but the findings to date have been controversial and inconsistent [16–19]. The International Agency for Research on Cancer, based on the epidemiological evidence of long-term mobile phone exposure, listed RF-EMF as only a possible human carcinogen (Group 2B) in 2011 [20].

Mobile phone associated exposures have also been linked with cognitive function and behavioural changes in children and adolescent populations [21–23]. Some people have been identified as “electro-hypersensitive (EHS)”, which they attribute to RF-EMF exposures [24, 25]. According to the WHO, most commonly reported symptoms of EHS include redness, tingling, and burning sensations (dermatological), fatigue, tiredness, concentration difficulties, dizziness, nausea, heart palpitation, and digestive disturbances (neurasthenic and vegetative); but this group of symptoms is not associated with any recognised syndrome [26]. Furthermore, current scientific evidence does not support any causal relationship between EHS and RF-EMF exposure [26]. Understanding human risks from RF-EMF exposures needs to be improved through the application of robust exposure assessment tools and methods [27, 28]. The utilization of better methods would enable us to reduce misclassification of exposure in epidemiological studies. The World Health Organization in 2010 emphasized the need for quantification of personal exposures from multiple RF-EMF sources and performance of rigorous human epidemiological studies [29].

The purpose of this review is to present and discuss state-of-the-art RF-EMF exposure assessment instruments, which can be used in human epidemiological studies.

Methods

A literature search was performed using MEDLINE, Scopus and Google Scholar databases during May 2014–March 2015. Key words used singly or in combination were radiofrequency-electromagnetic radiation exposures, radiofrequency-electromagnetic field exposure, personal dosimeters, personal exposimeters, software modified phones, hardware modified phones, and apps for mobile phone exposure. Only peer reviewed articles published in the English language since 1982 were considered including conference proceedings of the Bioelectromagnetics Society and the European BioElectromagnetics Association from the same period. In addition, relevant online information/publications of government agencies and of the RF-EMF monitor manufacturers were retrieved. Personal contact with the manufacturers was also made to update their product specifications (if any) and for permission to use pictures of their products.

Results

Personal RF-EMF exposure assessment has been a challenging task in human epidemiological studies. Various methods have been used to assess personal exposures. Assessment tools that have been previously employed and/or discussed in the literature include: questionnaires, job titles, years of phone use or subscription, estimated proximity to base stations, extent of use in moving vehicles, self-reported frequency and duration of phone use, indoor or outdoor use, billing records, network operator records, mobile phone battery charge and research diaries [27]. Recently, the assessment of personal and microenvironmental exposures from mobile phone base stations, Wi-Fi networks, FM radio, etc. by the use of exposimeters has been proposed. [28].

Self-reported wireless phone (mobile or cordless phone) use has been used as a proxy for RF-EMF exposure in past epidemiological studies [18, 19, 30], in order to investigate associations between mobile/cordless phone exposures and risk of brain or head tumours. This particular approach to exposure assessment is prone to misclassification and inaccurate risk estimates [27, 30, 31]. Similarly, mobile phone subscriptions were used as a proxy for exposure in the large Danish mobile phone users’ cohort [32]. This again is prone to inaccurate exposure assessment as phone owners and users can be different.

In recent years, significant progress has been made in exposure assessment science and technology as more sophisticated instruments have been continuously developed and tested. These tools can be broadly classified as mobile phone-based or exposure monitors that evaluate objective exposure data from near-field and far-field RF-EMF sources respectively. The examples of near-field sources include mobile/cordless handsets, computers/laptops and tablets with WLAN, and bluetooth. Far-field exposures include those from base stations, Wi-Fi hotspots/routers, and radio/TV broadcast stations.

Mobile phone based instruments

We found three smartphone-based applications (apps) [XMobiSens (Whist Lab, Institut Mines-Télécom/Orange, Paris, France) [33, 34]; Tawkon (Tawkon Ltd, Tel Aviv, Israel) [35], and Quanta Monitor (Cellraid, Oulunsalo, Finland) [36]; which run on smartphones and tablets to evaluate smart phone exposures. Also, there are two (non-smart) mobile phone-based instruments: Software Modified Phone (SMP) [37, 38] and Hardware Modified Phone (HMP) [39], which allow a mobile phone to have dual functionalities of phone and dosimeter. SMP is an ordinary handset that has additional dedicated software, which automatically keeps a record of information such as number of calls, duration of calls etc. On the other hand, HMP is a modified handset that has additional hardware connected to the battery.

The smart phone based-assessment tools, as well as hardware modified phones are illustrated in the Figs. 1 and 2 respectively.

Fig. 2 The rear view of a hardware modified phone (the battery is wired to special hardware inside the handset)

Exposimeters or exposure monitors

Exposimeters or exposure monitors are also available to measure the levels of environmental RF-EMF (in free space), and to estimate personal far-field exposures (with a body-worn exposimeter). Currently available and/or commonly used exposimeters include EME Spy 200 (SATIMO, Courtaboeuf, France) [40], ESM 140 (Maschek Electronik, Bad Wörishofen, Germany) [41], Narda exposimeters (Nardalert S3, RadMan, and RadMan XT) [Narda Safety Test Solutions, New York, USA] [42], ExpoM-RF (Fields at Work GmbH, Zürich, Switzerland) [43], and personal distributed exposimeters (PDEs) (Ghent University/iMinds, Ghent, Belgium) [44, 45], which are illustrated in the Figs. 3a, b, 4, and 5a, b respectively. The Narda exposimeters are broadband exposimeters, where as the others are narrowband. The characteristics of each of these instruments, their respective measured or estimated exposure parameters are summarized in Tables 1 and 2. The limitations of these devices, as well as other relevant characteristics will be discussed later in this paper.

Discussion

Assessment of exposure with minimal misclassification is the aim of researchers in epidemiological studies. A precise exposure measurement is always a challenging task, and therefore a good proxy of exposure is generally used in epidemiological studies. Each proxy of exposure will have limitations resulting in exposure misclassification. Therefore, validity of epidemiological studies also largely depends on the type of exposure assessment tool(s) chosen for a particular study. The exposure index of RF-EMF in such tools is determined by frequency and signal modulation, intensity of RF-EMF, and exposure duration [54].

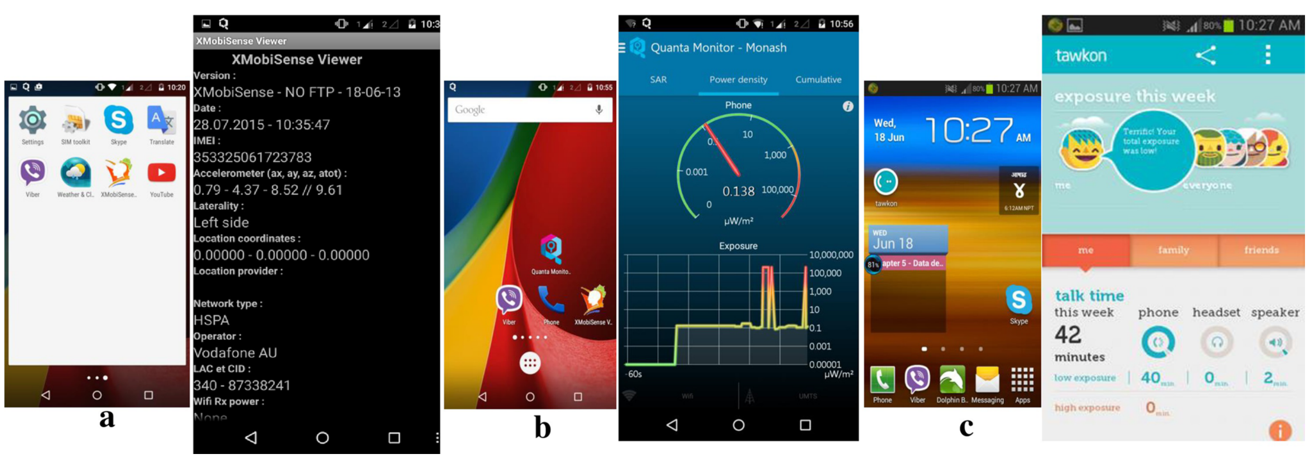

Fig. 1 The screenshots of **a** *XMobiSense* app, **b** *Quanta Monitor* app, and **c** *Tawkon* app (Courtesy: Prabhat Lamichhane, Monash University, Melbourne, Australia)

a b

Fig. 3 Exposimeters: **a** an *EME Spy 200* and, **b** *ESM 140*

a b c

Fig. 4 Narda exposimeters: **a** *Nardalert S3*, **b** *RadMan*, and **c** *RadMan XT*

Based on the distance from a RF-EMF emitting antenna to a human body, the exposures can be of far-field or near-field origin. The far-field starts at a distance of $2D^2/\lambda$ from a RF-EMF emitting source, where D is the largest dimension of the emitting antenna, and λ is the RF-EMF wavelength in air [55]. The far-field exposures are characterised by the uniform distribution of electric and magnetic fields over the dimension of the human body. Therefore, measuring either the electric or the magnetic field is sufficient to characterise the exposure from the far-field RF-EMF sources [55]. In near-field exposure, electric and magnetic fields are generally characterised by the non-uniform distribution of electric and magnetic fields over the dimension of the human body [55]. Mobile phone exposure essentially has two exposure components—transmitter (*Tx*) and receiver (*Rx*) power. The network connection from a mobile phone to a base station antenna(s) (i.e. uplink) is characterised by the *Tx* power, whereas, that from a base station antenna(s) to mobile phone (downlink) is characterised by the *Rx* power [56]. The *Tx* power values, which are the averaged actual power emitted by mobile phone, are much higher than the *Rx* power values [56].

The far-field RF-EMF exposures can be measured with exposimeters for a fixed location (e.g. site monitoring and spot measurements), and across different sites (e.g. microenvironment monitoring and personal monitoring) [28, 54]. The site/spot measurements provide information about far-field environmental RF-EMF exposure at a particular site for the duration of the measurement. Microenvironment monitoring provides personal exposure data across specified time periods, and provides a basis for comparison of the exposures across various study sites. Therefore, microenvironment monitoring is not a valid surrogate for personal or population exposure assessment [28]. Personal far-field exposure monitoring evaluates the exposures received by an individual across multiple locations and times. Environmental and personal exposures have been measured using various types of exposimeters in many countries [14, 47, 49, 50, 52, 53]. Time-activity diaries have been used to collect site and activity specific data [57]. The combined information from the exposimeters and the time-activity diaries have been used to characterise far-field associated personal exposures across various typical microenvironments [14, 15]. The near-field exposure from mobile phones has been generally evaluated using the in-built software or hardware of the phone. The cumulative personal RF-EMF exposure should ideally combine both far-field and near-field personal exposures over a considerable time. Personal exposure in human populations is mainly dominated by the exposure from the near-field RF-EMF sources. A recent study reported that the near-field sources account for 98.4 and 94 % of the total brain and the whole body doses respectively [52].

The majority of exposure assessment tools presented in this review evaluate data used to provide a surrogate for the specific absorption rates (SARs) from both near- and far-field RF-EMF exposures. SAR is a measure of the rate of

Fig. 5 **a** *ExpoM-RF* exposimeter, **b** A personal distributed exposimeter (2-front and 2-rear detection antennas) [Courtesy: Dr Arno Thielens, Ghent University/iMinds, Belgium]

Table 1 Types of mobile phone-based RF-EMF exposure assessment instruments and their respective characteristics

Type of tools	Parameters measured	Validation & applications
Smart phone-based applications		
XMobiSense	Network type, network operator, number of phone calls, duration of calls, laterality of usage, use of speaker phone or other hands-free kits, phone received power (dBm) for 2G, 3G, LTE, Wi-Fi networks, number of SMS, and amount of transmitted and received data (kB/s) [33, 34]	It has been recently validated [34]; useful for epidemiological studies
Tawkon	Duration of calls with/without using headset or hands-free [35]	There is no independent scientific validation of the tool; limited use for epidemiological studies
Quanta monitor	Average power density (μW/m^2) for the networks of GSM/UMTS/LTE/CDMA/EVDO, Wi-Fi (380 MHz –2.6 GHz), SAR (estimated); cumulative power density (μWh/m^2) (detection range 0.7 μV/m–3.2 V/m); exposure duration from phone and the networks [36]	There is no independent scientific validation of the tool; our group will be testing/using the tool; useful for epidemiological studies
Earlier phone-based instruments		
Software modified phone	Call time and date, output power level, radiofrequency used, cumulative emitted power, duration of calls, number of calls; captures dual band (900/1800 MHz) and tri band (900/1800/1900 MHz) frequencies [37, 38]	It is a validated tool [37, 38]; useful for epidemiological studies
Hardware modified phone	Number of calls, duration of calls, power output, power fluctuations, phone tilts in X, Y and Z planes with respect to the user's head [39]	It is a validated tool [39]; useful for epidemiological studies

GSM Global System for Mobile Communications, *UMTS* Universal Mobile Telecommunications System, *LTE* Long-Term Evolution, *CDMA* Code Division Multiple Access, *EVDO* Enhanced Voice-Data Optimized

energy absorption per unit mass of the biological tissue, and mathematically given as SAR (in W/kg) $= \sigma \times E^2/\rho$, where σ, E, and ρ are the tissue conductivity (S/m), the induced electric field or intensity (V/m) in the tissue of interest, and the tissue mass density (kg/m^3) respectively. One of the key applications of exposimeters is that whole-body or organ specific SAR can be estimated using the measured personal exposure data (in terms of power density) provided by exposimeters and a validated statistical multipath tool [54, 58]. Joseph et al. [58] used mean personal exposure data at various European microenvironments to estimate the whole-body mean SAR for a 1-year old child and adult male phantoms. The whole-body mean SAR at frequency *i* was estimated as, $SAR_i = a \times 377 \times (power\ density)_i$; the parameter '*a*' depends on the phantom type (e.g. adult or child), posture, the frequency bands, and the type of microenvironment considered [54]. The formula is only suited for far-field exposure contexts. Therefore, the method underestimates the SAR as the uplink exposures (e.g. from personal mobile phone), which constitute a considerable localised SAR, could not be estimated. Furthermore, body shielding would provide an underestimate of personal exposure (i.e. power density), which in turn, would again underestimate the whole-body SAR [58]. More recently, brain and whole body doses (mJ/kg) have been estimated for the adolescent population in Switzerland using the exposimeters' data and a modelling approach [52].

This review does not aim to include all the commercially available instruments such as broadband

Table 2 Types of commonly used exposimeters for RF-EMF far-field exposures and their respective characteristics

Exposimeter types	Frequency bands	Sampling intervals and data storage	Detection limits	Parameters measured	Sizes and weights	Battery lives	Measurement uncertainties	Validation & applications
EME Spy 200 (SATIMO monitor)	FM (87–107 MHz), TV3 (174–223 MHz), TETRA I (380–400 MHz), TETRA II (410–430 MHz) & TETRA III (450–470 MHz), TV4 & 5 (470–770 MHz), LTE 800 DL (791–821 MHz), LTE 800 UL (832–862 MHz), GSM + UMTS 900 UL (880–915 MHz), GSM + UMTS 900 DL (925–960 MHz), GSM 1800 UL (1710–1785 MHz), GSM 1800 DL (1805–1880 MHz), DECT (1880–1900 MHz), UMTS 2100 UL (1920–1980 MHz), UMTS 2100 DL (2110–2170 MHz), Wi-Fi 2G (2400–2483.5 MHz), LTE 2600 UL (2500–2570 MHz), LTE 2600 DL (2620–2690 MHz), WiMax (3300–3900 MHz), Wi-Fi 5G (5150–5850 MHz) [20 frequency bands]	4–255 s; 80,000 signals per measurement	Upper limit of 6 V/m (all frequencies); lower limits: 50 mV/m (FM radio), 10 mV/m (TETRA, TV4 & 5), 20 mV/m (TV3, WiMax, WiFi 5G), and 5 mV/m (the other frequencies)	Electric field strength (V/m)	168.5 mm × 79 mm × 49.7 mm; 440 g	>15 h (sampling interval 10 s), >6 h (sampling interval 4 s)	Frequency dependent; ±0.1–2.2 dB (vertical polarization); ±0.6–2.8 dB (horizontal polarization) [40]	The information about the use/validation of the exposimeter is not available; the previous EME Spy series were widely used for environmental and personal exposure assessments [46–48]; useful for epidemiological studies
ESM 140 (Maschek monitor)	GSM 900 UL (900 MHz), GSM 900 DL (935 MHz), GSM 1800 UL (1750 MHz), GSM 1800 DL (1850 MHz), DECT UL & DL (1895 MHz), UMTS UL (1950 MHz), UMTS DL (2140 MHz), and WLAN UL & DL (2440 MHz) [mid-range frequency given – 8 frequency bands]	0.5–10 s; 260,000 signals per measurement	10 mV/m – 70 V/m	Mean and maximum electric field strengths (V/m)	45 mm × 115 mm × 29 mm; 87 g	35 h	±2 dB (free field); ±4 dB (attached to the arm) [41]	The tool is validated and used to evaluate personal exposures [49]; useful for epidemiological studies
Nardalert S3	Frequencies in the range of 100 kHz–50 GHz, depending upon chosen standards (e.g. FCC, IEEE, SC6, ICNIRP)	1, 4, 5 per s, 1 per 10 s, 1 per 20 s, 1 per 60 s; 62,000 signals (4.3 h—43 days of total storage)	5–200 % of the standards; alarm threshold –10 to 200 % of the standards	Mean squared electric field strengths (V^2/m^2) (% of the standards)	117.1 mm × 82.6 mm × 31.8 mm; 230 g	25 h	+4.5/−3 dB (100 kHz–30 GHz), +2.5/−6 dB (30–50 GHz) (frequency sensitivity & polarisation uncertainty) [42]	The information about the use/validation of the exposimeter is not available; the tool may be useful particularly for occupational epidemiological studies; mostly used for the RF-EMF safety–monitoring of environmental (area) and personal exposures against the standards [42]

Table 2 continued

Exposimeter types	Frequency bands	Sampling intervals and data storage	Detection limits	Parameters measured	Sizes and weights	Battery lives	Measurement uncertainties	Validation & applications
RadMan/ RadMan XT	1 MHz–40 GHz	1 s, 2 s, 5 s, 10 s, 1 min and 3 min; 1638 signals (6 values per data logging interval point)	12.5, 25, 50 and 100 % of the standards rating of power density; alarm threshold—50 % of the standards	Maximum, minimum, and average values electric and magnetic field strengths (Simultaneous measurements, % of the standards)	37 mm × 41 mm × 163 mm; 130 g	200 h (LEDs and audio alarm off)	Magnetic field: ±3 dB (up to 1 GHz); electric field: ±3 dB (up to 3 GHz), +4/−3 dB (3–10 GHz), +6/−3 dB (10–18 GHz), +6/−10 dB (18–40 GHz) [42]	The tool is validated; useful particularly for occupational epidemiological studies [47, 48]; mostly used for the RF-EMF safety–monitoring of environmental (area) and personal exposures against the standards [42, 50, 51]
ExpoM-RF	FM (87.5–108 MHz), DVB-T (470–790 MHz), LTE 800 DL (791–821 MHz), LTE 800 UL (832–862 MHz), GSM 900 UL (880–915 MHz), GSM 900 DL (925–960 MHz), GSM 1800 UL (1710–1785 MHz), GSM 1800 DL (1805–1880 MHz), DECT (1880–1900 MHz), UMTS UL (1920–1980 MHz), UMTS DL (2110–2170 MHz), ISM 2.4 (2400–2485 MHz), LTE 2600 UL (2500–2570 MHz), LTE 2600 DL (2620–2690 MHz), WiMax (3400–3600 MHz), ISM (5150–5875 MHz) [16 frequency bands]	3–6000 s (steps of 0.5 s); 50 million signals	Upper limits: 3 V/m and 5 V/m (WiMax and all frequencies respectively); lower limits: 20 mV/m (FM radio), 50 mV/m (ISM 5.8), 3 mV/m (LTE and WiMax), and 5 mV/m (the other frequencies)	Root mean square electric field strength (V/m)	160 mm × 80 mm × 40 mm; 320 g	10 h (sample interval 3 s, GPS and Bluetooth on); the battery life can be extended with longer sampling intervals	–1.2 dB (GSM DL 900) to +1 dB (LTE), –1.2 dB to + 1 dB (the other frequencies) [43]	The tool is validated [52]; useful for epidemiological studies—evaluation of personal and environmental exposures [43, 52]
Personal distributed exposimeter (PDE)	GSM 900 DL (915–960 MHz), DECT, Wi-Fi (2400–2483.5 MHz)	1 s; 693,589 signals	23.7 mV/m–237 V/m (upper right front antenna), 4.4 mV/m–44 V/m (lower left front antenna), and 2 mV/m–20 V/m (central back antenna) (GSM 900 DL 3-antenna PDE)	Root mean square electric field strength (V/m) or average power density (W/m^2)	100 mm × 125 mm × 10 mm (GSM 900 DL each antenna), 70 mm × 70 mm × 4 mm (Wi-Fi each antenna); weight: <200 gm (each antenna)	20 h	95 % prediction interval: 7–7.4 dB (GSM 900 DL) [44]; 50 % prediction interval: 3 dB (Wi-Fi) [53]	It is validated for GSM 900 DL and Wi-Fi [44, 53]; useful for epidemiological studies—evaluation of personal exposures

TERA Terrestrial Trunked Radio, *DECT* Digital Enhanced Cordless Telecommunications, *DL* Downlink, *UL* Uplink, *ISM* Industrial, Scientific and Medical, *DVB–T* Digital Video Broadcasting–Terrestrial, *WiMAX* Worldwide Interoperability for Microwave Access, *WLAN* Wireless Local Area Network, *FCC* The Federal Communications Commission, *IEEE* The Institute of Electrical and Electronics Engineers, *SC6* Safety Code 6 (Canada), *ICNIRP* The International Commission on Non-Ionizing Radiation Protection exposimeters and spectrum analysers and apps but rather focuses on reviewing the most commonly used instruments and apps that could be potentially used in future epidemiological studies. These instruments and apps have their strengths and limitations as discussed here.

Comparison of instruments: strengths, limitations and recommendations

Smart phone apps or instruments

XMobiSense measures the exposures from mobile (2G, 3G and LTE) and Wi-Fi networks. The app provides the data on the number of calls, number of SMS, duration of use, laterality of use, mobile network *Rx* power (in dBm), Wi-Fi *Rx* power (in dBm), the amount of transmitted and received data of 2G, 3G and Wi-Fi (kilobyte/s) [34, Sarrebourse T, Orange Labs, France, personal communication 27/07/2015]. These are important parameters that can be used to characterise the mobile phone exposures. The measurement uncertainties for *Rx* power are phone dependent. The laterality of phone use, measured by its accelerometer, can be correlated with the brain exposure and related to location of the brain tumours occurrence. The data collected by the app can be downloaded from the mobile phone to a computer for direct analysis. Alternatively, the data file can also be directly sent from the user's mobile phone to a file transfer protocol server from which the exposure data can be later retrieved for analysis. XMobiSens could therefore be of benefit for future epidemiological research despite some limitations. There is limited information available in the published scientific literature about its use in epidemiological studies [33, 34]. XMobiSense has been used in the Mobi-Kids substudy: Mobi–Expo, to evaluate RF-EMF exposure from smart phones, and validate the exposure related responses from participants across 15 countries worldwide [34]. Validation studies are important to compare the agreement between actual phone use and participants' recall of phone use [30, 34, 57]. Feedback on its attributes is expected to be available soon. The app is also limited since it cannot measure the exposure associated with the Wi-Fi *Tx* power of the mobile phone. This will obviously underestimate the exposures from the phones. Furthermore, the app's application is also limited to Android-based smart phones or tablets.

Tawkon claims that its technology is calibrated by SATIMO, an FCC certified radiofrequency laboratory in the USA [35]. The technology apparently consists of an internal measurement system that records information about network type, band-GSM, UMTS, CDMA, channel, signal strength and phone model. Furthermore, the app claims to be able to calculate the phone's radiation output levels and the corresponding estimated SAR values on FCC near-field exposure standards [35]. These particular claims are questionable because the SAR levels critically depend on the distance of the phone to the user and its orientation. Therefore, further scientific validation is necessary to examine the veracity of the claim. Tawkon has an alert function for the user, which is activated when the exposure from the mobile phone exceeds a pre-determined level. This alert function then suggests the user engage alternate means to minimise exposure (e.g. use of a speaker or headset). These functions would confound use in an epidemiological study as it would lead to changed behaviour during the study unless the feature can be turned off. Furthermore, the app can only provide very limited useful exposure data (such as 'duration of call'), which is inadequate for future epidemiological studies. We could not find any published epidemiological studies involving the Tawkon app as an instrument for exposure assessment.

The new app Quanta Monitor, has key features which enable it to evaluate *Rx* and *Tx* powers (μW/m^2) to and from the mobile phone and Wi-Fi networks [36]. The use of a proximity sensor helps the phone to evaluate the cumulative exposure (μWh/m^2) only when the phone is placed close to the body (i.e. up to 5 mm away from the body). The exposure data is provided in terms of hourly/-daily/weekly/monthly total exposure (μWh/m^2) and exposure time due to phone (i.e. calls, data, Wi-Fi) and network (i.e. cellular, Wi-Fi). The estimated measurement uncertainties for the *Rx* and *Tx* powers are reported to ±1 dB and ±3 dB respectively (Niemi P, Cellraid, Personal communication 29/07/2015). The Quanta Monitor developers claim that they have also developed an algorithm that can estimate SAR. Publication of independent validation of the app is lacking and necessary prior to use in future epidemiological studies. The exposure data collected by the app is automatically stored in a cloud server. While issues of data security remain important and challenging in cloud computing [59], such an option, despite its ease and potential cost-effectiveness, might not prove to be a sound tool for human epidemiological studies. The app does not report the data on the number of calls and SMS, which would be necessary parameters in future studies. Furthermore, the tool shares a common limitation of the smart phone apps- in only being applicable to Android-based smart phones or tablets.

A study using XMobiSens has recently demonstrated that the app can be efficiently used to collect smart phone RF-EMF exposure data in epidemiological studies [34]. The inability of measuring the *Tx* power by XMobiSens, however, can be assessed with Quanta Monitor. The assessment of exposure from *Tx* power has been a prime interest in epidemiological studies. Therefore, use of both apps simultaneously would provide more complete exposure assessment in future studies. There is also a common limitation of these apps—none of them is able to detect signals from TETRA or DVBT.

Earlier phone-based instruments

Early model SMPs have been used to measure the data on number of calls, duration of calls, output power level, cumulative emitted power, etc. [37, 38]. They are easy to use since they only require the insertion of a SIM card. Typically, the SMP memory can store up to of eight hours of conversation [60]. The data can be downloaded later to a computer using a simple software. Once the data are downloaded, the phone is again ready for further use to collect and store further data. Therefore, long-term monitoring of exposure is possible with SMPs [38]. Typical sampling intervals of 0.12 and 2.5 s are available, as is an auto setting (with a minimum sampling interval of 1 s) that varies according to changes in frequency and power variables [38, 60]. The interpretation of exposure measured by the SMPs should be done cautiously as they do not discriminate power output during normal calls or hands-free modes. Furthermore power fluctuation is not measured by SMP, though it is well captured by more sophisticated HMPs [27].

In the early model HMP's, data (number of calls, duration of calls, power output, power fluctuations, phone tilts) is recorded and automatically stored while the phone is in use, and is transferred to a computer following routine battery charging. The important parameter power fluctuation, which is not measured by the SMPs, is well captured by HMPs [27]. The data collected by HMPs can be used later in estimating SAR levels to the head region due to the use of mobile phones. In terms of SAR dosimetry, the HMPs comply with the ICNIRP standards [39]. An important limitation of HMPs is the need for extensive laboratory calibration prior to use [27].

In past epidemiological studies, quantitative mobile phone near-field RF-EMF exposure assessments have been reported for both SMPs [30, 37, 38, 60–63] and HMPs [39, 64]. Unfortunately, the SMP technology-based exposure assessment is limited to non-smart phones or models before 3G service [30] and this is also the case with HMPs. This is clearly a major practical limitation of SMPs and HMPs since most people are using smart phones. It may be useful for future epidemiological research to develop the HMP technology for smart phones, and other near-field exposure devices, if possible.

Exposimeters or exposure monitors

The EME Spy 200 is derived from earlier SATIMO/EME Spy models. The previous EME Spy models are the most commonly used exposimeters in environmental and personal RF-EMF dosimetry. Therefore, it is important to draw comparisons between EME Spy 200 and the other exposimeters currently available.

EME Spy 200 can detect a total of 20 frequency bands compared to ESM 140 and ExpoM-RF, which can detect 8 and 16 frequency bands respectively. The Nardalert S3, RadMan, and RadMan XT cover a wide spectrum of RF-EMF frequencies, whereas the PDE so far is only able to measure 2 frequency bands. Therefore, EME Spy 200 and Nardalert S3, RadMan/RadMan XT seem to be the best choice if measurement of a wide spectrum of RF-EMF is required. It is important to note that EME Spy 200, ESM 140 and ExpoM-RF can discriminate the individual contribution of various frequency bands as well as providing the total exposure levels. However, this is not the case with Nardalert S3 and RadMan/RadMan XT, where only an overall exposure level is provided. Moreover, Nardalert S3, RadMan, and RadMan XT are primarily used in RF-EMF safety programs—monitoring of environmental (area) and personal RF-EMF exposure levels against reference levels in standards from ICNIRP, IEEE/FCC and Safety Code 6 (Canada) etc. Nevertheless, they can still be useful for epidemiological studies particularly where exposure from a wide range of RF-EMF sources is anticipated. Exposimeters should ideally discriminate up- and down-link band specific exposures. This is possible with the EME Spy 200, the ESM 140 and the ExpoM-RF exposimeters. The older ESM 140 had a limitation of low selectivity between the up- and down-link frequency channels, and therefore the frequency bands needed to be combined to assess exposures [49, 65]. Importantly, signal discrimination is essential when frequency-dependent biological or health effects are to be investigated in future studies. These limitations are not applicable to PDEs as they are only able to measure GSM 900 DL and Wi-Fi signals [44, 53].

An important parameter of exposimeters is the sampling interval. This varies from one exposimeter to another such as 0.5–10 s for the ESM 140 and the Nardalert S3, 1 s for the PDE, 4–255 s for the EME Spy 200, and 3–6000 s for the ExpoM-RF. Furthermore, the Nardalert S3 has a variable sampling interval of 1, 2, 5, 10 s, 1 and 3 min; whereas the RadMan/RadMan XT sampling interval ranges from 1 s to 3 min. The selection of sampling interval mainly depends on the intended duration of the data collection (i.e. the number of signals collected), type of signals, and battery life. The maximum number of signals that can be collected per measurement with the exposimeters can be compared (in an increasing order) as; RadMan/RadMan XT < Nardalert S3 < EME Spy 200 < ESM 140 < PDE < ExpoM-RF (Table 2). The sampling intervals and operation of other accessory applications such as Bluetooth, GPS in exposimeters critically influence the battery life. Therefore, comparasion of exposimeters solely on the basis of the battery life is not straightforward. A long-term exposure assessment in epidemiological studies ideally demands a continuous measurement to be taken over a few weeks to months. Currently available exposimeters are only able to record signals for up to a week before they need to be recharged. Clearly, exposimeters with a reasonably long battery life are preferable from this viewpoint.

The sensitivity of exposimeters is very important particularly in terms of lower detection threshold for various frequency bands relevant to environmental and personal exposures. Table 2 shows that the lower detection limits may vary considerably from one exposimeter to another, depending on the frequency band to be considered. RF-EMF signals in many environmental settings can be very weak. To date, this has led to a substantial proportion of reported measurements below the lower detection threshold [15, 48, 66]. The likelihood of encountering weak signals needs to be considered when selecting a suitable exposimeter, so that the percentage of measurements below the limit of detection is minimized. The relevance of upper detection threshold can be important where relatively higher levels of exposures are anticipated such as occupational exposures. The threshold for the Nardalert S3 and the RadMan/RadMan XT are specified in terms of the IEEE, SC6, and ICNIRP standards, as these dosimeters are primarily used for occupational RF-EMF exposure monitoring and safety.

The size and weight of exposimeters are important parameters in the context of epidemiological studies that may involve children. Comparison of the available exposimeters is as follows (in an increasing order of size and weight); ESM 140 $<$RadMan/RadMan XT $<$ Nardalert S3 $<$ ExpoM-RF $<$ EME Spy 200. All of the exposimeters, except for ESM 140 and the PDE, are worn or carried. In general, it is most important that exposimeters have small physical dimensions and be lightweight. Young children, in particular, may not be ready to carry relatively larger/heavier exposimeters for any considerable time period. Therefore, exposure assessment with children should be preferably performed with smaller and lighter weight exposimeters such as the ESM 140, wherever possible.

The RF-EMF signal detection probes of the EME Spy 200, the ExpoM-RF and the RadMan/RadMan XT are isotropic or tri-axial. Isotropy characteristics of a sensor allow measurements with the same intensity of signals to be performed irrespective of the measurement direction. The ESM 140 has a non-isotropic electric field antenna. Its antenna achieves isotropy only when the exposimeter is attached to the upper arm of the wearer [28]. Therefore its usability is compromised when the exposimeter is detached from the arm such as during sleep at night or during other activities such as swimming and bathing. Clearly, for epidemiological purposes, exposimeters with isotropic sensors are preferable for personal RF-EMF exposure assessment.

The measurement uncertainties associated with exposimeters differ and are frequency specific (Table 2). For instance, the EME Spy 200 has specified frequency- and polarisation-specific uncertainties they are well documented. However, the ESM 140 specifies it's measurement uncertainties in terms of unique values for free space measurement and for when it is attached to the users arm for all frequency bands.

None of the exposimeters, except the ExpoM-RF, have inbuilt GPS geolocation functionality which automatically captures information relevant to the location of the particular measurement. Geo-location functionality, aided with the Android smartphone app, can be used with EME Spy 200. The GPS or geolocation function in exposimeters is important [28], since it precisely identifies the location of the measurements. It can be useful when repeated measurements with high spatial accuracy of the same place or environment are required for a long term assessment. The GPS data also provides a valuable input parameter for any potential exposure modelling, and might also help validate the geo-location related information noted in time-activity diaries [28]. The geo-location/GPS of the EME Spy 200/ExpoM-RF can be helpful when repeated site or area specific environmental monitoring needs to be performed.

The PDE system is in the prototype stage and is still under development. It is integrated within a garment that utilizes different combinations of textile antennas (2, 3 or 4) distributed over the body. The PDE integrated in the wearable clothing is lightweight and flexible. This exposimeter device has been tested for GSM 900 DL and Wi-Fi frequencies [43, 53], and the developers plan to release a model in the near future. Recent trials have been conducted by the developers of the PDE, with 3-antennas (2-front and 1-back) to measure personal exposure across various microenvironments. The prototype device does not appear user-friendly as the antennas and associated circuit (wires and battery) are not integrated into clothing but temporarily attached to the wearer. This gives the appearance of an incomplete device. Feasibility testing with the view for use in future epidemiological studies are on-going. Major limitations of this experimental device are that it cannot capture a broad range of the RF-EMF frequency bands and has limited battery life.

The RadMan and the RadMan XT are best suited where measurement of electric and magnetic field exposures are relevant—for instance, occupational exposures in the broadcast and telecommunication industries. In these industries it is important to evaluate both electric- and magnetic field exposures as the workers are likely to spend significant time close to the RF-EMF sources whilst performing maintenance work. In particular, the RadMan models have been employed in evaluating occupational exposures from magnetic fields for maintenance workers in broadcast and telecommunication installations [50, 51]. RADARs (frequency range 10 MHz–300 GHz) used in the defence, navigation, weather prediction, etc. are of concern due to high potential occupational exposure [67, 68]. In these workplaces, use of the RadMan exposimeter with a 30 ms averaging time is recommended compared to the RadMan/RadMan XT.

Clearly, recommendations regarding consideration of use of a particular exposimeter depends upon the measurement context or environment. The characteristics of an exposimeter discussed above should be carefully considered when choosing one exposimeter in preference to another. This should be done in the context of the population or site specific characteristics in which exposure monitoring is to be carried out.

Gaps in exposure assessment and implications for epidemiological research

The exposure assessment tools for near-field devices are only able to measure electric fields. The near-field electric field exposure expressed in power density does not provide a realistic measure of accurate body exposure. Ideally, exposure in terms of SAR (W/kg) should be reported for the near-field devices [69]. However, the estimation of SAR in human populations for epidemiological studies is not yet practically possible. In addition, low frequency pulsed magnetic fields are also induced into tissues because of battery current pulses during the transmission of mobile phone signal [70]. Therefore, it is essential that future mobile phone exposure assessment tools focus on the measurement of electric and magnetic field exposures. The contribution of magnetic field exposure from near-field RF-EMF source (e.g. mobile phones) may not be of much significance to be relevant in epidemiological studies [71]. However, the magnetic field exposures should be evaluated for developing a comprehensive exposure matrix [70, 71]. Nowadays, the other near-field RF-EMF devices such as laptops, tablets, iPads and cordless phones have also contribute to RF-EMF exposure and need to be included in exposure assessment for epidemiological research [52]. Therefore prospective exposure assessment tools need to also include the contribution to overall exposure from these devices. Due to the lack of apps which can evaluate personal exposures from iPhone, additional selection bias will occur in future epidemiological studies. Similarly, exposure from cordless phones constitutes a significant near-field RF-EMF exposure [12, 72, 73]. The development of tools for exposure assessment for these devices are urgently needed.

Currently a major limitation of all exposimeters is that they are unable to measure a considerable proportion of RF-EMF signals that fall below their lower detection limits [15, 48, 67]. To compensate researchers have resorted to the use of statistical approaches such as robust regression on order statistics or naïve methods for each frequency band [57, 74]. This suggests that there is clearly a need to improve exposimeter capabilities to reduce their lower detection thresholds further [67]. In addition, a regular calibration with realistic signals is necessary for field instruments to avoid any possible systematic errors during measurement [75].

The uncertainties of exposimeters include body shielding, calibration, frequency response of probes, sensitivity variations and measurement errors [15]. An exposimeter worn on the body tends to under- or over-estimate the actual ambient RF-EMF exposure levels [15, 75–77]. The measured exposure levels essentially depend on whether the exposimeter is worn on the side of the incident RF-EMF or the orientation of body exposimeter with respect to the RF-EMF direction. This is because the human body absorbs, reflects, and refracts incident RF-EMF [78]. The body also casts a shadow of incident RF-EMF on an exposimeter placed on the shielded side [79] resulting in data uncertainties. It has been recommended that frequency- and exposimeter-dependent correction factors (taking calibration, elevation angle, and body shielding into account) should be applied to maximise accuracy of exposure measurements [66, 75]. It has also been suggested that using two exposimeters (one on the front and the other on the rear of the body) may help reduce the measurement inaccuracies associated with body shielding effects [76, 77]. This should allow the simultaneously measured on-body electric field intensity data of the two exposimeters to be combined to calculate a composite average of the body exposure levels. Thielens et al. [80] have shown that wearing two on-body calibrated exposimeters (one on either side of the hip) provided accurate measurements. However, in epidemiological studies this would be costly and impractical since subjects would be required to wear two exposimeters continuously for considerable time periods. The PDE system with multiple RF-EMF acquisition nodes proposes to reduce the measurement uncertainties related to body shielding. With further development so that a wide range of frequency bands can be captured, this device would be very useful in human exposure assessment and should overcome problems inherent in arm worn monitors.

The use of near-field RF-EMF exposure devices during the measurement may influence the measured levels of far-field RF-EMF exposure levels. For instance, higher personal far-field RF-EMF exposures are recorded when users make a call with mobile or cordless phones [14]. A mobile phone, particularly a smart phone, in standby mode tends to increase personal RF-EMF exposure levels as it regularly updates on its location [47]. A cordless phone in standby mode is also likely to have similar impacts on exposimeter measurements. Therefore, a clear distinction regarding the presence and use of the near-field RF-EMF emitting devices (e.g. mobile or cordless phones) should be noted while undertaking and reporting exposimeter RF-EMF levels [47].

Modelling approaches to evaluate environmental RF-EMF exposures are also available [81, 82]. It has been demonstrated that modelling helps in estimating whole body and organ specific SARs resulting from near-field and far-field exposures [83]. Iskra et al. [84] applied the finite-difference time-domain method to estimate average whole body average SAR levels for far-field exposures. A key advantage of modelling is that it can provide an exposure assessment at the cost of randomly distributed errors [54]. Furthermore, it removes the requirement of dependency on the participants for collecting estimated exposure data. Therefore, it is expected that modelling will prove itself as a useful tool for exposure assessment in the future. Sophisticated exposure models demand a large amount of accurate input data of RF-EMF transmitter and transmission parameters, building location and characteristics, and human behaviour characteristics [63]. However, the modelling approach could be challenging when retrospective exposure assessment using historic data is required [14].

Currently available exposimeters have limitations as they generally provide time-weighted average exposure data without any information on modulation and proportion of peak signals above a threshold [15]. The exposimeters' algorithms may not account for variation of power flux density/electric field intensity in accordance with the RF-EMF frequency, the body posture and the body type. Furthermore, the exposure data retrieved through the application of exposimeters assumes that the exposure measurements are performed in far-field scenarios, which may not always be the case. Therefore, the estimation of exposures using the exposimeters will suffer from random errors, and hence has limitations for its application in epidemiological studies. This can be a major limitation as the population exposures from the intermediate frequency range (300 Hz–10 MHz), including that from AM radio, are suggested to be significant [15, 85]. Furthermore, it is likely that terahertz frequency (>300 GHz) will be available for future technologies. This will lead to the demand for monitoring of environmental and population exposures from these technologies. Therefore, there may be an unrealistic expectation that exposimeters will be required to detect exposure to all of these RF-EMF signals. The ultimate challenging goal of RF-EMF exposure assessment in epidemiology remains to be the estimation of cumulative population doses from all relevant near- and far-field RF-EMF sources [86].

Conclusion

We have described currently available RF-EMF exposure assessment instruments which provide objective RF-EMF exposure data. These instruments provide numerous potential benefits to epidemiological studies compared to previously employed exposure assessment tools such as questionnaires and billing records. Nonetheless, there are limitations associated with the instruments we have described, which should be considered in instrument selection. Future development needs to provide the capability to assess exposures from cordless phones, iPhones and laptops devices. Exposimeters also need improvement in terms of size and weight reduction, longer battery life, the number of frequency bands that can be measured, and lower detection limits.

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References

1. Vecchia P, Matthes R, Ziegelberger G et al (2009) Exposure to high frequency electromagnetic fields, biological effects and health consequences (100 kHz–300 GHz). International Commission on Non-Ionizing Radiation Protection (Oberschleissheim, Germany)
2. Markov M, Grigoriev YG (2013) Wi-Fi technology-an uncontrolled global experiment on the health of mankind. Electromagn Biol Med 32:200–208
3. Allen S (1991) Radiofrequency field measurements and hazard assessment. J Radiol Prot 11:49–62
4. Miyakoshi J (2009) Cellular biology aspects of mobile phone radiation. In: Lin JC (ed) Advances in electromagnetic field in living systems: health effects of cell phone radiation, vol 5. Springer, New York, pp 1–33
5. IEEE (2006) IEEE standard for safety levels with respect to human exposure to radio frequency electromagnetic fields, 3 kHz to 300 GHz. IEEE Std C95.1™-2005 (Revision of IEEE Std C95.1-1991)
6. Berg-Beckhoff G, Blettner M, Kowall B et al (2009) Mobile phone base stations and adverse health effects: phase 2 of a cross-sectional study with measured radio frequency electromagnetic fields. Occup Environ Med 6:124–130
7. Ha M, Im H, Lee M, Kim HJ, Kim BC, Gimm YM, Pack JK (2007) Radio-frequency radiation exposure from AM radio

transmitters and childhood leukemia and brain cancer. Am J Epidemiol 166(3):270–279
8. Redmayne M, Smith E, Abramson MJ (2013) The relationship between adolescents' well-being and their wireless phone use: a cross-sectional study. Environ Health 12:90
9. Rothman KJ, Chou CK, Morgan R et al (1996) Assessment of cellular telephone and other radio frequency exposure for epidemiologic research. Epidemiology 7:291–298
10. Foster KR, Moulder JE (2013) Wi-Fi and health: review of current status of research. Health Phys 105:561–575
11. ICT Facts and Figures (2014) International Telecommunication Union Geneva 20, Switzerland. http://www.itu.int/en/ITU-D/Statistics/Documents/facts/ICTFactsFigures2014-e.pdf. Accessed 17 August 2014
12. Redmayne M (2013) New Zealand adolescents' cellphone and cordless phone user-habits: are they at increased risk of brain tumours already? A cross-sectional study. Environ Health 12:5
13. Hardell L, Carlberg M (2012) Use of mobile and cordless phones and survival of patients with glioma. Neuroepidemiology 40:101–108
14. Frei P, Mohler E, Neubauer G et al (2009) Temporal and spatial variability of personal exposure to radio frequency electromagnetic fields. Environ Res 109:779–785
15. Gajšek P, Ravazzani P, Wiart J et al (2013) Electromagnetic field exposure assessment in Europe radiofrequency fields (10 MHz–6 GHz). J Expo Sci Environ Epidemiol 1–8
16. Hardell L, Carlberg M, Hansson Mild K (2013) Use of mobile phones and cordless phones is associated with increased risk for glioma and acoustic neuroma. Pathophysiology 20:85–110
17. Interphone Study Group (2011) Acoustic neuroma risk in relation to mobile telephone use: results of the Interphone international case–control study. Cancer Epidemiol 35:453–464
18. Benson VS, Pirie K, Schuz J et al (2013) Mobile phone use and risk of brain neoplasms and other cancers: prospective study. Int J Epidemiol 42:792–802
19. Coureau G, Bouvier G, Lebailly P et al (2014) Mobile phone use and brain tumours in the CERENAT case-control study. Occup Environ Med 71:514–522
20. Baan R, Grosse Y, Lauby-Secretan B et al (2011) Carcinogenicity of radiofrequency electromagnetic fields. Lancet Oncol 12:624–626
21. Thomas S, Benke G, Dimitriadis C et al (2010) Use of mobile phones and changes in cognitive function in adolescents. Occup Environ Med 67:861–866
22. Divan HA, Kheifets L, Obel C et al (2012) Cell phone use and behavioural problems in young children. J Epidemiol Commun Health 66:524–529
23. Abramson MJ, Benke GP, Dimitriadis C et al (2009) Mobile telephone use is associated with changes in cognitive function in young adolescents. Bioelectromagnetics 30:678–686
24. Havas M (2013) Radiation from wireless technology affects the blood, the heart, and the autonomic nervous system. Rev Environ Health 28:75–84
25. Levitt BB, Lai H (2010) Biological effects from exposure to electromagnetic radiation emitted by cell tower base stations and other antenna arrays. Environ Rev 18:369–395
26. The World Health Organization (2005) Electromagnetic fields and public health. Electromagnetic hypersensitivity. http://www.who.int/peh-emf/publications/facts/fs296/en/. Accessed 25 October 2015
27. Inyang I, Benke G, Mckenzie R et al (2008) Comparison of measuring instruments for radiofrequency radiation from mobile telephones in epidemiological studies: implications for exposure assessment. J Exposure Sci Environ Epidemiol 18:134–141
28. Röösli M, Frei P, Bolte J et al (2010) Conduct of a personal radiofrequency electromagnetic field measurement study: proposed study protocol. Environ Health 9:23
29. van Deventer E, van Rongen E, Saunders R (2011) WHO research agenda for radiofrequency fields. Bioelectromagnetics 32:417–421
30. Inyang I, Benke G, Morrissey J et al (2009) How well do adolescents recall use of mobile telephones? Results of a validation study. BMC Med Res Methodol 9:36
31. Repacholi MH, Lerchl A, Röösli M et al (2012) Systematic review of wireless phone use and brain cancer and other head tumors. Bioelectromagnetics 33:187–206
32. Frei P, Poulsen AH, Johansen C et al (2011) Use of mobile phones and risk of brain tumours: update of Danish cohort study. BMJ 343:d6387
33. Wiart J, Sarrebourse T, Varsier N et al (2014) Use of apps for collecting information for exposure assessment. Proc Joint Annual Meeting of the Bioelectromagnetics Society and European Bioelectromagnetics Association, CapeTown, South Africa, 8–13 June 2014
34. Goedhart G, Vrijheid M, Wiart J et al (2015) Using software-modified smartphones to validate self-reported mobile phone use inyoung people: a pilot study. Bioelectromagnetics. doi:10.1002/bem.21931
35. Tawkon (2014). http://tawkon.com/. Accessed 17 August 2014
36. Cellraid Products (2014). http://cellraid.com/products.php#quantamonitor. Accessed 12 January 2015
37. Berg G, Schuz J, Samkange-Zeeb F, Blettner M (2005) Assessment of radiofrequency exposure from cellular telephone daily use in an epidemiological study: German validation study of the international case–control study of cancers of the brain–Interphone–study. J Expo Anal Environ Epidemiol 15:217–224
38. Vrijheid M, Mann S, Vecchia P et al (2009) Determinants of mobile phone output power in a multinational study: implications for exposure assessment. Occup Environ Med 66:664–671
39. Inyang I, Benke G, McKenzie R et al (2009) Use of hardware modified phones for exposure assessment in health studies in Australia: verification of compliance with standards. Australas Phys Eng Sci Med 32:62–67
40. SATIMO (2014) Microwave Vision Group (Courtaboeuf, France). http://www.satimo.com/content/products. Accessed 12 November 2014
41. Maschek Electronik (2014) Maschek Electronik (Bad Wörishofen, Germany). http://www.maschek.de/de/. Accessed 12 November 2014
42. Narda Safety Test Solutions (2014) Narda Safety Test Solutions (New York, USA). http://www.narda-sts.us/products_main.php. Accessed 12 November 2014
43. Introducing ExpoM—A personal RF exposure meter (2014) Fields at Work GmbH (Zürich, Switzerland). http://www.fieldsatwork.ch/. Accessed 12 November 2014
44. Thielens A, De Clercq H, Agneessens S et al (2013) Personal distributed exposimeter for radio frequency exposure assessment in real environments. Bioelectromagnetics 34:563–567
45. Thielens A, Vanveerdeghem P, Agneessens S et al. (2014) Whole-body Averaged SAR Assessment Using a Personal, Distributed Exposimeter. Proceedings of Joint Annual Meeting of the Bioelectromagnetics Society and European Bioelectromagnetics Association CapeTown, South Africa, 8–13 June 2014
46. Urbinello D, Huss A, Beekhuizen J et al (2014) Use of portable exposure meters for comparing mobile phone base station radiation in different types of areas in the cities of Basel and Amsterdam. Sci Total Environ 468–469:1028–1033
47. Urbinello D, Röösli M (2013) Impact of one's own mobile phone in stand-by mode on personal radiofrequency electromagnetic field exposure. J Expo Sci Environ Epidemiol 23:545–548
48. Juhász P, Bakos J, Nagy N et al (2011) RF personal exposimetry on employees of elementary schools, kindergartens and day

nurseries as a proxy for child exposures. Prog Biophys Mol Biol 107:449–455
49. Thomas S, Kuhnlein A, Heinrich S et al (2008) Personal exposure to mobile phone frequencies and well-being in adults: a cross-sectional study based on dosimetry. Bioelectromagnetics 29:463–470
50. Cooper TG, Allen SG, Blackwell RP et al (2004) Assessment of occupational exposure to radiofrequency fields and radiation. Radiat Prot Dosimetry 111:191–203
51. Chauvin S, Gibergues ML, Wuthrich G et al (2009) Occupational exposure to ambient electromagnetic fields of technical operational personnel working for a mobile telephone operator. Radiat Prot Dosimetry 136:185–195
52. Roser K, Schoeni A, Bürgi A et al (2015) Development of an RF-EMF exposure surrogate for epidemiologic research. Int J Environ Res Public Health 12:5634–5656
53. Thielens A, Agneessens S, De Clercq H et al (2015) On-body calibration and measurements using a personal, distributed exposimeter for wireless fidelity. Health Phys 108:407–418
54. Röösli M and Vienneau D (2014) Epidemiology of electromagnetic fields. In: Röösli M (ed). Epidemiological exposure assessment. CRC Press Taylor & Francis Company, pp 35–55
55. Lin JC (2007) Dosimetric comparasion between different quantities for limiting exposure in the RF band: rationale and implications for guidelines. Health Phys 92:547–553
56. Gati A, Conil E, Wong M-F, Wiart J (2010) Duality between uplink local and downlink whole-body exposures in operating networks. IEEE Trans Electromagn Compat 52:829–836
57. Frei P, Mohler E, Bürgi A et al (2010) Classification of personal exposure to radio frequency electromagnetic fields (RF-EMF) for epidemiological research: evaluation of different exposure assessment methods. Environ Int 36:714–720
58. Joseph W, Frei P, Röösli M et al (2012) Between-country comparison of whole-body SAR from personal exposure data in Urban areas. Bioelectromagnetics 33:682–694
59. Pearson S, Benameur A (2010) Privacy, security and trust issues arising from cloud Computing. Proceedings of cloud computing technology and science (CloudCom) 2010 IEEE 2nd international conference, Indianapolis, 30 November–3 December 2010
60. Ardoino L, Barbieri E, Vecchia P (2004) Determinants of exposure to electromagnetic fields from mobile phones. Radiat Prot Dosim 111:403–406
61. Vrijheid M, Cardis E, Armstrong BK et al (2006) Validation of short term recall of mobile phone use for the Interphone study. Occup Environ Med 63:237–243
62. Erdreich LS, Van Kerkhove MD, Scrafford CG et al (2007) Factors that influence the radiofrequency power output of GSM mobile phones. Radiat Res 168:253–261
63. Kelsh MA, Shum M, Sheppard AR et al (2011) Measured radiofrequency exposure during various mobile-phone use scenarios. J Expo Sci Environ Epidemiol 21:343–354
64. Inyang I, Benke G, McKenzie R et al (2010) A new method to determine laterality of mobile telephone use in adolescents. Occup Environ Med 67:507–512
65. Thomas S, Kühnlein A, Heinrich S et al (2008) Exposure to mobile telecommunication networks assessed using personal dosimetry and well-being in children and adolescents: the German MobilEe-study. Environ Health 7:55
66. Neubauer G, Cecil S, Giczi W et al (2008) Final Report on the project C2006-07: evaluation of the correlation between RF dosimeter reading and real human exposure ARC-IT-0218. http://www.emf.ethz.ch/archive/var/SB_Neubaue_pre25f.pdf. Accessed 12 December 2014
67. Joseph W, Goeminne F, Vermeeren G et al (2012) Occupational and public field exposure from communication, navigation, and radar systems used for air traffic control. Health Phys 103:750–762
68. Singh S, Kapoor N (2015) Occupational EMF exposure from radar at X and Ku frequency band and plasma catecholamine levels. Bioelectromagnetics. doi:10.1002/bem.21925
69. Bergqvist U, Friedrich G, Hamnerius Y, et al (2000) Mobile telecommunication base stations–exposure to electromagnetic fields. Report of a short term mission within COST-244bis
70. Jokela K, Puranen L, Sihvonen AP (2004) Assessment of the magnetic field exposure due to the battery current of digital mobile phones. Health Phys 86:56–66
71. Calderón C, Addison D, Mee T et al (2014) Assessment of extremely low frequency magnetic field exposure from GSM mobile phones. Bioelectromagnetics 35:210–221
72. Redmayne M, Inyang I, Dimitriadis C et al (2010) Cordless telephone use: implications for mobile phone research. J Environ Monit 12:809–812
73. Guxens M, van Eijsden M, Vermeulen R et al (2013) Maternal cell phone and cordless phone use during pregnancy and behaviour problems in 5-year-old children. J Epidemiol Community Health 67:432–438
74. Röösli M, Frei P, Mohler E et al (2008) Statistical analysis of personal radiofrequency electromagnetic field measurements with nondetects. Bioelectromagnetics 29:471–478
75. Bolte JF, van der Zande G, Kamer J (2011) Calibration and uncertainties in personal exposure measurements of radiofrequency electromagnetic fields. Bioelectromagnetics 32:652–663
76. Iskra S, McKenzie RJ, Cosic I (2011) Monte Carlo simulations of the electric field close to the body in realistic environments for application in personal radiofrequency dosimetry. Radiat Prot Dosimetry 147:517–527
77. Iskra S, McKenzie RJ, Cosic I (2010) Factors influencing uncertainty in measurement of electric fields close to the body in personal RF dosimetry. Radiat Prot Dosimetry 140:25–33
78. Knafl U, Lehmann H, Riederer M (2008) Electromagnetic field measurements using personal exposimeters. Bioelectromagnetics 29:160–162
79. Mann S (2010) Assessing personal exposures to environmental radiofrequency electromagnetic fields. CR Phys 11:541–555
80. Thielens A, Agneessens S, Verloock L et al (2015) On-body calibration and processing for a combination of two radio-frequency personal exposimeters. Radiat Prot Dosimetry 163:58–69
81. Beekhuizen J, Vermeulen R, van Eijsden M et al (2014) Modelling indoor electromagnetic fields (EMF) from mobile phone base stations for epidemiological studies. Environ Int 67:22–26
82. Joseph W, Vermeeren G, Verloock L et al (2010) Estimation of whole-body SAR from electromagnetic fields using personal exposure meters. Bioelectromagnetics 31:286–295
83. Lauer O, Frei P, Gosselin MC et al (2013) Combining near- and far-field exposure for an organ-specific and whole-body RF-EMF proxy for epidemiological research: a reference case. Bioelectromagnetics 34:366–374
84. Iskra S, McKenzie R, Cosic I (2009) Absorption in human body at 900 MHz for oblique incidence of plane wave. Electron Lett 45:602–604
85. Henderson S, Tjong L, Wijayasinghe D (2014) Survey of radiofrequency radiation levels across Melbourne. Proceedings of the 39th Australasian Radiation Protection Society Conference, Hobart, 26–29 June 2014
86. Dürrenberger G, Fröhlich J, Röösli M et al (2014) EMF monitoring–concepts, activities, gaps and options. Int J Environ Res Public Health 11:9460–9479

Chapter 3. Measuring personal exposure from 900 MHz mobile phone base stations

Overview

In the previous chapter, I have identified objective tools for RF-EMF exposure assessment and recommended the tools that could be employed in assessing RF-EMF exposures in human populations. This and the next two chapters present the contexts in which these robust tools may be used in evaluating human exposures to RF-EMF in various settings.

The RF-EMF exposure from mobile phone base stations, particularly 900 MHz downlink frequency band, is one of the key contributors to telecommunication related RF-EMF exposure to human populations (69-72, 74). This chapter discusses the measurement of personal RF-EMF exposures from mobile phone base station 900 downlink. In contrast to the conservative approach to personal RF-EMF measurement (i.e. use of non-calibrated single body-attached exposimeter), this chapter explores the feasibility of conducting exposure assessment with a novel approach and tool – the use of a three antenna personal distributed exposimeter (PDE). The use of a single body-worn exposimeter resulted in a considerable amount of measurement uncertainties due to body-shielding (88, 89, 91). In this novel approach of applying the PDE, three antennas of the PDE simultaneously measured exposure, which subsequently provided a composite measure exposure to the human body thereby minimising the measurement uncertainties (92). The exposure assessments were carried out across different microenvironments in Melbourne, Australia, and in/around Ghent, Belgium. The chapter also compares the exposure levels for selected microenvironments in the two countries.

The paper concluded that it was feasible to employ the PDE to estimate personal exposure to 900 MHz downlink. Exposures in the GSM 900 MHz frequency band across most of the microenvironments in Australia were significantly lower than the exposures across the microenvironments in Belgium. The measured exposure levels were far below the general public reference levels recommended in the guidelines of the International Commission on Non-Ionizing Radiation Protection and the Australian Radiation Protection and Nuclear Safety Agency.

Declaration for Thesis Chapter 3

Manuscript: **Bhatt CR,** Thielens A, Redmayne M, Abramson MJ, Billah B, Sim MR, Vermeulen R, Martens L, Joseph W, Benke G. Measuring personal exposure from 900 MHz mobile phone base stations in Australia and Belgium using a novel personal distributed exposimeter. *Environment International* 2016, 92–93: 388–397.

Declaration by candidate

In the case of Chapter 3, the nature and extent of my contribution to the work was the following:

Nature of contribution	**Extent of contribution (%)**
Study design, data collection, data analysis, manuscript preparation and editing, and revision of submitted manuscript	80%

The following co-authors contributed to the work. Where co-authors are students at Monash University, the extent of their contribution in percentage terms is stated:

Names	**Nature of contribution**
Arno Thielens	Data collection, data analysis and interpretation, development of manuscript, manuscript editing and revision of submitted manuscript
Mary Redmayne	Data interpretation, manuscript editing, revision of submitted manuscript, and supervision
Michael J.	Data interpretation, manuscript editing, revision of submitted manuscript, and

Abramson	supervision
Baki Billah	Data analysis and interpretation, and development of manuscript
Malcolm R. Sim	Study concept and design, study funding, data interpretation, manuscript editing and revision of submitted manuscript
Roel Vermeulen	Study concept and design, study funding, data interpretation, manuscript editing and revision of submitted manuscript
Luc Martens	Data interpretation, development of manuscript, manuscript editing and revision of submitted manuscript
Wout Joseph	Data collection, data analysis and interpretation, development of manuscript, manuscript editing and revision of submitted manuscript
Geza Benke	Study concept and design, study funding, data interpretation, manuscript editing, revision of submitted manuscript and supervision

The undersigned hereby certify that the above declaration correctly reflects the nature and extent of the candidate's and co-authors' contribution to this work.

Candidate's Signature		
	[redacted]	Date 28/04/2017

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Full Length Article

Measuring personal exposure from 900 MHz mobile phone base stations in Australia and Belgium using a novel personal distributed exposimeter

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ABSTRACT

The aims of this study were to: i) measure personal exposure in the Global System for Mobile communications (GSM) 900 MHz downlink (DL) frequency band with two systems of exposimeters, a personal distributed exposimeter (PDE) and a pair of ExpoM-RFs, ii) compare the GSM 900 MHz DL exposures across various microenvironments in Australia and Belgium, and iii) evaluate the correlation between the PDE and ExpoM-RFs measurements. Personal exposure data were collected using the PDE and two ExpoM-RFs simultaneously across 34 microenvironments (17 each in Australia and Belgium) located in urban, suburban and rural areas. Summary statistics of the electric field strengths (V/m) were computed and compared across similar microenvironments in Australia and Belgium. The personal exposures across urban microenvironments were higher than those in the rural or suburban microenvironments. Likewise, the exposure levels across the outdoor were higher than those for indoor microenvironments. The five highest median exposure levels were: city centre (0.248 V/m), bus (0.124 V/m), railway station (0.105 V/m), mountain/forest (rural) (0.057 V/m), and train (0.055 V/m) [Australia]; and bicycle (urban) (0.238 V/m), tram station (0.238 V/m), city centre (0.156 V/m), residential outdoor (urban) (0.139 V/m) and park (0.124 V/m) [Belgium]. Exposures in the GSM 900 MHz frequency band across most of the microenvironments in Australia were significantly lower than the exposures across the microenvironments in Belgium. Overall correlations between the PDE and the ExpoM-RFs measurements were high. The measured exposure levels were far below the general public reference levels recommended in the guidelines of the ICNIRP and the ARPANSA.

1. Introduction

The exposure of humans to radiofrequency-electromagnetic fields (RF-EMFs) is inevitable, due to the omnipresent RF-EMF sources in the modern environment. There are public concerns for potential health effects caused by the use of RF-EMF associated technologies, mobile phones and base stations (Kim et al., 2014; Tjong et al., 2015; Wiedemann et al., 2014). Furthermore, there is currently a strong need for quantification of personal exposures using objective measures for current and future human epidemiological studies (van Deventer et al., 2011).

The personal exposures from far-field RF-EMF sources, including mobile phone base stations, can be evaluated by performing personal measurements in various microenvironments using exposimeters (Dürrenberger et al., 2014; Joseph et al., 2010; Röösli et al., 2010; Urbinello et al., 2014a). However, exposure evaluations with exposimeters still have limitations (Bhatt et al., 2016), which give rise to measurement uncertainties. The uncertainties can reach up to 25–30 dB (Bolte et al., 2011; Iskra et al., 2011; Neubauer et al., 2010) and include shielding effects of the human body, the multidirectional nature of the incident RF-EMFs, residual calibration, the frequency response of the exposimeter, and the inability to detect signals below the lower detection limits, etc. (Bolte et al., 2011; Gajšek et al., 2015; Iskra et al.,

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2011; Mann, 2010; Neubauer et al., 2010). Measurement uncertainties in personal exposimetry could be reduced by employing on-body calibrated exposimeters (Thielens et al., 2015a).

A personal distributed exposimeter (PDE) with multiple RF-EMF antennas, placed on the body, has been developed recently in order to reduce measurement uncertainties related to shielding effects and directionality of the signal (Thielens et al., 2013, 2015a, 2015b; Vanveerdeghem et al., 2015). The PDE systems have been tested to measure far-field exposures from the Global System for Mobile communications (GSM) 900 MHz downlink (DL) and Wi-Fi networks (Thielens et al., 2013, 2015b). In the GSM 900 MHz DL band, the first prototype was developed using three on-body antennas (Thielens et al., 2013), but was not used for actual measurements. A second generation prototype was used for actual exposure measurements (Vanveerdeghem et al., 2015). This system consists of four on-body antennas matched with complementary receiver electronics and is currently the only system available for PDE measurements, which consequently can only consider the GSM 900 MHz DL band at this moment.

Several European studies indicate that mobile phone base stations are a major source of whole body exposure to RF-EMF (Bolte and Eikelboom, 2012; Frei et al., 2009; Gajšek et al., 2015; Joseph et al., 2010; Urbinello et al., 2014b, 2014c; Vermeeren et al., 2013). More specifically, mobile phone base stations are a dominant exposure source to the whole body in urban outdoor environments and on public transport (Joseph et al., 2010; Urbinello et al., 2014a, 2014b).

While much of the information about personal RF-EMF exposure comes from the studies conducted in Europe, similar information from Australia or elsewhere is lacking. There are only limited data on environmental exposure from mobile phone base stations, particularly at locations close to the base stations, that have been reported in Australia (Radio Frequency National Site Archive, 2015; Rowley and Joyner, 2012; Henderson and Bangay, 2006). The utilization of mobile phone technology in Australia has increased substantially during the last two decades. This is similar to what has occurred in Europe, including Belgium, and USA (ACMA paper, 2015; ACMA communications report, 2014). The demands of increased mobile phone signal coverage and signal capacity largely contributed to measured increases in outdoor environmental exposures of 20% to 57% in three European cities (including Gent, Belgium) over the course of one year (Urbinello et al., 2014a). Therefore, a comparative study of personal RF-EMF exposure using similar study protocols, involving countries in Europe and elsewhere was needed.

The purposes of this study were: i) to measure personal exposure in the GSM 900 MHz downlink (DL) frequency band with two systems of exposimeters, the PDE (a novel exposimeter) and a pair of ExpoM-RFs, ii) to compare the exposure levels for selected microenvironments in the two countries, and iii) to assess the correlation between the PDE and ExpoM-RFs measurements.

2. Materials and methods

2.1. Study areas

The study was conducted in urban, suburban, and rural areas in Australia and Belgium (Fig. 1). The measurements were performed by one person (CRB) during 16th April–8th May and 27th March–6th April 2015, respectively. The study regions in Australia included Victoria, and mainly covered the Greater Melbourne region, and a rural site (Cathedral Range State Park). Similarly, Gent and Mol, the provinces of East Flanders and Antwerp respectively, in the Flemish region of Belgium were covered in the study. We considered a region to be urban when the population density was >400 people per square kilometre (Joseph et al., 2010).

A total of 34 matched microenvironments (17 in Australia and 17 in Belgium) were chosen to evaluate personal exposures. A microenvironment is a spatial compartment where a human subject spends time and his/her personal RF-EMF exposure is evaluated for that specific duration (Röösli et al., 2010; Urbinello et al., 2014a, 2014b). The selected microenvironments were similar to those employed in various previous studies (Bolte and Eikelboom, 2012; Frei et al., 2009; Joseph et al., 2010; Röösli et al., 2010; Urbinello et al., 2014a, 2014b). The characteristics of each microenvironment, its spatial characteristics, and the activities undertaken therein by the subject are summarized in Table 1 in Appendix A. The microenvironments were mainly of two types: stationary or mobile. The stationary microenvironments remained fixed while the subject moved around in the microenvironment, whereas the mobile microenvironments moved around during the data collection while the subject generally remained stationary. The mobile microenvironments included bus, train, tram, car and bicycle, whereas stationary microenvironments included the rest, except for subway station/ride, which was a mixed microenvironment.

2.2. On-body calibration procedure

2.2.1. The PDE system

The PDE system was used to perform personal exposure measurements in the GSM 900 downlink (DL) band (925–960 MHz). The PDE system was a collection of three body-worn antennas (see Fig. 2) (2 anterior and 1 posterior) tuned to the mobile phone GSM 900 MHz DL frequency band. The PDE was connected to complementary receiver electronics (Vanveerdeghem et al., 2015) that registered the received

Fig. 1. Maps of a) Australia and b) Belgium showing Melbourne and Gent respectively (Sources: https://commons.wikimedia.org, and http://www.bbc.co.uk/, respectively).

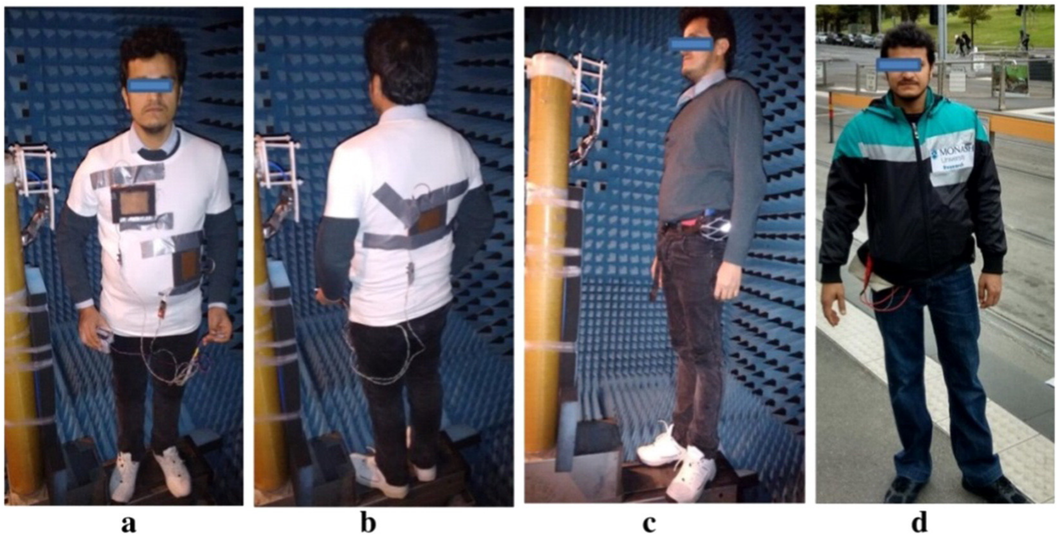

Fig. 2. The human subject performing i) an on-body calibration of the PDE (figures a & b), and ii) ExpoM-RFs (figure c), in Gent, Belgium, ii) exposure measurement at a site in Melbourne, Australia (figure d).

power on the antennas. The E_{inc} (incident electric-field strength) can be determined from the received power on the PDE, using the effective antenna aperture (*AA*) of the set of antennas (Thielens et al., 2015b, 2015c). On-body calibration was performed to determine the *AA*.

2.2.2. The ExpoM-RFs system

The ExpoM-RFs measured electric field strengths (E_{body}) in 16 different frequency bands, including GSM 900 MHz DL. This study only dealt with GSM 900 MHz DL frequency band. ExpoM-RF 64 and ExpoM-RF 40 were used in the calibration process.

2.2.3. The calibration procedure

In this study, we used established on-body calibration procedures (Thielens et al., 2013, 2015a, 2015b, 2015c; Vanveerdeghem et al., 2015). The calibration took place in an anechoic chamber with a transmitting antenna (T_X) on one side of the chamber and a rotational platform on the other side. The T_X emitted a constant output power at 942.5 MHz, thus inducing RF-EMFs that were incident on the rotational platform on which the subject could stand.

The subject (a 35-year-old male subject; height 163 cm and mass 60 kg) participated in the on-body calibration in order to conduct subsequent field measurements. The subject did not carry a mobile phone and did not have any metal objects attached to his body during calibration. The calibration procedure is further described in Appendix B.

2.3. Exposure assessment

The exposure measurement system consisted of the PDE (prototype) system (Gent University/iMinds, Gent, Belgium) and the two above-mentioned ExpoM-RFs (Fields at Work GmbH, Zürich, Switzerland). The PDE antennas were attached to a *T*-shirt; 2 front antennas (1 over the right chest, the other on the left abdominal area), and 1 posterior antenna on the central back (Fig. 2). The antennas were wired to a battery and operated with an on/off switch. Each

Table 2
Personal exposures (E_{rms} in V/m) across various microenvironments in Australia and Belgium [median (25th, 75th percentiles) and range (min, max)].

Microenvironments	Australia		Belgium	
	Median (25th, 75th percentiles)	Range (min, max)	Median (25th, 75th percentiles)	Range (min, max)
Residential outdoor (urban)	0.044 (0.029, 0.075) [2,a]	0.017, 0.197	0.139 (0.094, 0.197) [1,a]	0.022, 0.494
Residential indoor (urban)	0.019 (0.016, 0.024) [2,a]	0.008, 0.047	–	–
Office indoor (urban)	0.018 (0.016, 0.021) [2,a]	0.010, 0.046	0.032 (0.027, 0.039) [2,a]	0.010, 0.091
Park (urban)	0.051 (0.029, 0.065) [2,a]	0.019, 0.156	0.124 (0.091, 0.162) [2,a]	0.034, 0.458
City centre	0.248 (0.102, 0.324) [2,ab]	0.006, 0.647	0.156 (0.115, 0.182) [1,a]	0.057, 0.278
Library (urban)	0.049 (0.036, 0.062) [2,a]	0.014, 0.124	0.110 (0.088, 0.145) [1,a]	0.038, 0.278
Shopping centre (urban)	0.021 (0.019, 0.025) [1,a]	0.015, 0.115	0.028 (0.025, 0.034) [1,a]	0.015, 0.204
Railway station (urban)	0.105 (0.074, 0.117) [2,ab]	0.042, 0.331	0.034 (0.023, 0.169) [1,a]	0.015, 0.534
Tram station (urban)	0.038 (0.030, 0.060) [2,a]	0.007, 0.075	0.238 (0.204, 0.267) [1,a]	0.139, 0.622
Bicycle (urban)	0.017 (0.007, 0.041) [2,ab]	0.007, 0.221	0.238 (0.169, 0.300) [1,a]	0.053, 0.784
Bicycle (rural/suburban)	–	–	0.012 (0.010, 0.013) [1,a]	0.009, 0.035
Bus (urban)	0.124 (0.065, 0.213) [2,a]	0.027, 0.555	0.028 (0.019, 0.049) [2,b]	0.007, 0.556
Car (urban/suburban)	0.006 (0.006, 0.006) [1,a]	0.006, 0.049	0.041 (0.023, 0.065) [2,ab]	0.007, 0.387
Car (rural/suburban)	–	–	0.016 (0.013, 0.020) [1,a]	0.009, 0.070
Tram (urban)	0.041 (0.035, 0.058) [2,a]	0.006, 0.197	0.055 (0.029, 0.124) [1,a]	0.017, 0.441
Train	0.055 (0.030, 0.115) [2,ab]	0.011, 0.534	0.020 (0.017, 0.027) [1,a]	0.011, 0.084
Subway station/ride (urban)	0.031 (0.027, 0.039) [1,a]	0.015, 0.312	–	–
Residential outdoor (rural/suburban)	0.006 (0.006, 0.006) [2,a]	0.006, 0.051	0.014 (0.011, 0.044) [2,a]	0.010, 0.088
Residential indoor (rural/suburban)	–	–	0.017 (0.016, 0.019) [2,a]	0.013, 0.031
Mountain/forest (rural)	0.057 (0.049, 0.061) [1,b]	0.012, 0.068	–	–

1 = single measurement, 2 = repeated measurement; a = 3-antennas' data, b = 2 antennas' data; ab = 3 antennas' data in one measurement and 2 antennas' data in the other measurement.

antenna collected the signals simultaneously. Two ExpoM-RFs were attached to the lateral sides of the hip (one each side) using travellers' money belts.

A light jacket was worn by the subject to cover both exposimeter systems while carrying out the field measurements (Fig. 2). The subject did not have any metal objects attached to his body during the data collection. A diary was maintained in order to record information on activities undertaken during data collection and descriptions of the microenvironments. All measurements were performed during the daytime (9:45 am–6:00 pm) or evening hours (6:00 pm–11:00 pm) on weekdays, except the measurements of residential outdoor and residential indoor (rural/suburban) in Belgium, which were performed during the weekends (2:30–2:45 pm and 11:00–11:15 pm respectively). The RF-EMF measurements during the daytime and evening on weekdays were expected to provide the highest values of exposure (Joseph et al., 2010).

Each measurement duration was 15 min per microenvironment. Urbinello et al. (2014a, 2014b) have employed similar measurement duration to monitor personal exposures. A smart phone was used to monitor measurement time during the measurements; it was in flight mode to prevent it from transmitting and receiving signals during data collection. The measurement interval for the PDE and the ExpoM-RFs were chosen to be 1 and 3 s, respectively.

On average, the PDE collected a total of 900 samples on each antenna per microenvironment measurement session. Similarly, each ExpoM-RF collected 300 data samples per measurement. Most of the microenvironment measurements were performed twice (Table 1 in Appendix A) to check exposure variability.

In Australia, the measurements in three microenvironments involved three and two antennas' data at the time of the first and second measurements, respectively; whereas a microenvironment involved measurement with two antennas (Table 2). Similarly, a microenvironment in Belgium involved two antennas' data during both measurements, and the other microenvironment involved three and two antennas' data during the first and the second measurements respectively (Table 2). The detection range of the PDE (with on-body calibration) was 5.9 mV/m–59 V/m. The detection range for the ExpoM-RFs for GSM 900 MHz DL reported in the datasheet of the devices (without on-body calibration) was 5 mV/m–5 V/m. After an on-body calibration, the detection range of the ExpoM-RFs was estimated at 10 mV/m–10 V/m. Both devices measured the root mean square electric field strengths (E_{rms}) in V/m. The measured data of the PDE were then processed using the corresponding *AA* and detection limit of the relevant pair of antennas. Similarly, geometric mean of the on-body calibration factors of the ExpoM-RFs was used to process the measured ExpoM-RFs data, see Section 3.1.

2.4. Data processing and statistical analysis

The PDE data output provided the incident electric fields for a geometric mean of the given combination of antennas. Geometric means of the electric field signals obtained with two ExpoM-RFs were computed over time within the selected sample intervals using the formula; $Geometric\ mean = (E_{ExpoM\text{-}RF40} \times E_{ExpoM\text{-}RF64})^{1/2}/0.51$, where 0.51 is the correction for the presence of the body (i.e. a division by the average response of the pair of ExpoM-RFs). The normality of the geometric mean data of the PDE and ExpoM-RFs for each microenvironment and each measurement session (i.e. measurement 1 and measurement 2) were examined by Shapiro-Wilk tests of both untransformed and log-transformed data. In addition, visual inspection of histograms and the normal Q-Q plots was also performed. Measurements 1 and 2 represented the first and the second (repeated) measurements, respectively.

Medians (25th and 75th percentiles) and ranges (minimum, maximum) of the electric field strengths were calculated from the geometric means of the PDE and ExpoM-RFs data obtained from the combination of antennas and two ExpoM-RFs, respectively. The values measured by the individual antennas of the PDE and individual ExpoM-RF were not considered in this study. The exposures measured with the ExpoM-RFs were only used while evaluating the agreement between two devices' measurements.

Personal exposure levels were described by summary statistics of the electric field strengths measured with the PDE. The personal exposures across similar microenvironments in Australia ($n = 14$) and Belgium ($n = 14$) were compared. Six microenvironments were excluded from the comparison: residential indoor (urban), subway station/ride (urban), mountain/forest (rural) in Australia ($n = 3$), and bicycle (rural/suburban), residential indoor (rural/suburban) and car (rural/suburban) in Belgium ($n = 3$). These were excluded because each comparable corresponding microenvironment in the other country was not assessed.

The Shapiro-Wilk test and evaluation of histograms and normal Q-Q plots indicated that none of the microenvironments followed a normal or lognormal distribution of the personal exposure electric field levels. Therefore Wilcoxon rank sum tests were performed on the exposure data of the compared microenvironments in order to examine whether the exposures across those microenvironments in Australia and Belgium were different. The assessment of exposure variability during the first and second measurements was done by performing Wilcoxon rank sum tests. Thirteen microenvironments in Australia and 6 microenvironments in Belgium, which had repeated measurements, were evaluated.

The correlations between the PDE and ExpoM-RFs measurements were evaluated on the median exposure data of 34 microenvironments (17 in each country). The evaluation was performed also for 21 stationary (11 in Australia and 10 in Belgium) and 13 mobile microenvironments (6 in Australia and 7 in Belgium).

For all statistical tests, the $p < 0.05$ (two sided) was considered as statistically significant. All data analyses were carried out using MATLAB R2015a (The MathWorks Inc., Natick, Massachusetts, USA) or STATA ver13.1 (StataCorp, College Station, TX, USA).

3. Results

3.1. Calibration of the exposimeter systems

The median antenna aperture of the PDE worn on the body, calculated over 100 repetitions of the same processing, was found to be 1.05 cm^2 (inter quartile range 1.04 cm^2–1.06 cm^2). The value of the prediction interval (PI_{50}) for antenna aperture of the PDE was 3.3 dB.

The median responses of the ExpoM-RFs worn on the body and the geometric average of both ExpoM-RFs, calculated over 100 repetitions of the same processing, were found to be 0.502 (inter quartile range 0.502–0.503) [ExpoM-RF 40], 0.533 (inter quartile range 0.532–0.534) [ExpoM-RF 64], and 0.507 (inter quartile range 0.507–0.508) [geometric average of two ExpoM-RFs].

The values of PI_{50} on the response of the ExpoM-RFs were 5.9 dB (ExpoM-RF 40), 3.6 dB (ExpoM-RF 64) and 4.2 dB for the geometric average of the two ExpoM-RFs.

3.2. Descriptive statistics

The E_{rms} values of all the measured signals were found to be above the lower measurable threshold of the PDE. Table 2 below summarizes the personal exposure levels across different microenvironments in Australia and Belgium.

In Australia, the five highest median exposure levels (from mobile phone base stations) measured were: city centre (0.248 V/m), bus (0.124 V/m), railway station (0.105 V/m), mountain/forest (rural) (0.057 V/m), and train (0.055 V/m). Similarly, the five lowest median exposures measured were: car (urban/suburban) (0.006 V/m),

Table 3
Evaluation of the variability in personal exposure measurements [medians at M_1 (measurement 1) and M_2 (measurement 2) in V/m].

Microenvironments	Countries	Median (25th, 75th percentiles) at M_1	Median (25th, 75th percentiles) at M_2	*P values
Residential outdoor (urban)	Australia [a]	0.055 (0.034, 0.098)	0.041 (0.026, 0.062)	<0.001
Residential indoor (urban)	Australia [a]	0.017 (0.014, 0.031)	0.019 (0.016, 0.023)	0.17
Office indoor (urban)	Australia [a]	0.017 (0.016, 0.019)	0.016 (0.015, 0.023)	0.46
Office indoor (urban)	Belgium [a]	0.033 (0.028, 0.044)	0.034 (0.029, 0.041)	0.29
Park (urban)	Australia [a]	0.046 (0.030, 0.055)	0.055 (0.028, 0.070)	<0.001
Park (urban)	Belgium [a]	0.106 (0.078, 0.156)	0.106 (0.084, 0.134)	0.91
City centre	Australia [ab]	0.324 (0.289, 0.386)	0.081 (0.015, 0.162)	<0.001
Library (urban)	Australia [a]	0.055 (0.047, 0.062)	0.055 (0.049, 0.065)	0.17
Railway station (urban)	Australia [ab]	0.117 (0.105, 0.132)	0.081 (0.057, 0.106)	<0.001
Tram station (urban)	Australia [a]	0.031 (0.028, 0.035)	0.060 (0.053, 0.062)	<0.001
Bicycle (urban)	Australia [ab]	0.035 (0.020, 0.057)	0.007 (0.007, 0.007)	<0.001
Bus (urban)	Australia [a]	0.115 (0.053, 0.204)	0.134 (0.069, 0.238)	<0.001
Bus (urban)	Belgium [b]	0.046 (0.024, 0.069)	0.021 (0.018, 0.030)	<0.001
Car (urban)	Belgium [ab]	0.057 (0.044, 0.088)	0.022 (0.014, 0.038)	<0.001
Tram (urban)	Australia [a]	0.041 (0.036, 0.049)	0.036 (0.029, 0.053)	<0.001
Train	Australia [ab]	0.058 (0.024, 0.137)	0.057 (0.033, 0.102)	0.024
Residential indoor (rural/suburban)	Belgium [a]	0.019 (0.017, 0.021)	0.015 (0.015, 0.016)	<0.001
Residential outdoor (rural/suburban)	Australia [a]	0.006 (0.005, 0.006)	0.006 (0.005, 0.006)	0.22
Residential outdoor (rural/suburban)	Belgium [a]	0.047 (0.037, 0.057)	0.011 (0.011, 0.012)	<0.001

a = 3-antennas' data, b = 2 antennas' data; b = 2 antennas' data; ab = 3 antennas' data in one measurement and 2 antennas' data in the other measurement,
* P values <0.05 statistically significant different exposure levels.

residential outdoor (rural/suburban) (0.006 V/m), bicycle (urban) (0.017 V/m), office indoor (urban) (0.018 V/m), and residential indoor (urban) (0.019 V/m).

In Belgium, the five highest median exposures measured were: bicycle (urban) (0.238 V/m), tram station (0.238 V/m), city centre (0.156 V/m), residential outdoor (urban) (0.139 V/m), and park (0.124 V/m). Similarly, the five lowest exposure levels measured were: bicycle (rural/suburban) (0.012 V/m), residential outdoor (rural/suburban) (0.014 V/m), car (rural/suburban) (0.016 V/m), residential indoor (rural/suburban) (0.017 V/m), and train (0.020 V/m).

3.3. Comparison of exposure levels in Australia and Belgium

We found that personal exposures across most of the microenvironments in Australia were significantly lower ($p < 0.05$) than the exposure across the microenvironments in Belgium. However, there were a few microenvironments where the exposure in Australia was higher ($p < 0.05$) than the corresponding exposure in Belgium. For instance, the city centre results in Melbourne were significantly higher ($p < 0.001$) than the exposure level at the city centre of Gent, as were exposures in the Melbourne train and during a bus ride, than those in Gent.

3.4. Evaluation of the variability of exposures

Table 3 shows the results of the Wilcoxon rank sum tests that was were performed to evaluate if the repeated measurements provided similar exposure levels. The analysis showed that the majority of the microenvironments (13 of 19) provided significantly different median exposure levels at the measurements 1 and 2, suggesting that both measurements had highly varied exposures. The microenvironments demonstrating similar exposures at both measurements were: residential indoor (urban), office indoor (urban), library (urban), and residential outdoor (rural/suburban) [Australia], and office indoor (urban) and park (urban) [Belgium].

Spatial matching of the repeated stationary microenvironmental measurements was ensured by walking across the same area and towards the same direction. In case of the repeated mobile microenvironments, the spatial matching was accomplished by sitting/standing at the same spot/around the same positions with respect to window and carriage dimension. All mobile microenvironment measurements, except for car (urban) and bus (urban) in Belgium, were performed on exactly the same routes. The temporal matching, for most of the measurements, was ensured by performing the measurements (1st and 2nd) at similar times of the day, such as morning, evening or night.

3.5. Correlation between the PDE and the ExpoM-RFs measurements

The overall Spearman correlation coefficient for all microenvironments was 0.63 ($p < 0.001$). Similarly, the correlation coefficients for stationary and mobile microenvironments were 0.71 ($p < 0.001$) and 0.28 ($p = 0.24$), respectively.

4. Discussion

We have reported the personal far-field RF-EMF exposures from the GSM 900 MHz down-link frequency band across the various microenvironments in Australia and Belgium, using a novel on-body calibrated PDE system. Monitoring of exposures across various microenvironments, including those investigated in our work, is one of the approaches to assess human exposure (Dürrenberger et al., 2014; Joseph et al., 2010; Röösli et al., 2010; Urbinello et al., 2014a).

4.1. Exposure characteristics in Australia and Belgium

The personal exposure levels experienced across various microenvironments varied according to the location and type of microenvironment. Previous studies also found variation in exposure across various microenvironments (Bolte and Eikelboom, 2012; Frei et al., 2009; Joseph et al., 2010; Urbinello et al., 2014a). Spatial factors, such as the location of the measurement sites (urban, suburban, rural, outdoor, indoor etc.), distance to nearby base stations; temporal factors (e.g. day, time and season when the measurements were performed), and existing mobile phone traffic are likely to impact the levels of far-field personal exposures (Bolte and Eikelboom, 2012; Joseph and Verloock, 2010; Manassas et al., 2012; Urbinello et al., 2014b; Vermeeren et al., 2013).

The exposure levels found in our study were well below the reference levels for the general public as provided in the guidelines of the International Commission on Non-Ionizing Radiation Protection (ICNIRP, 1998) and the Australian Radiation Protection and Nuclear Safety Agency (Radiation Protection Standard, 2002). The mean exposures in Australia measured were in the range of 0.02–3.65% of the reference level, whereas those in Belgium were in the range of 0.03–2.73% of the reference level. The reference level for GSM 900 MHz DL specified by the guidelines is equivalent to 42 V/m [$Erms = 1.37 \times (f)0.5$ V/m] at

942.5 MHz. However, it should be borne in mind that these guidelines are designed to protect against immediate RF-EMF effects from elevated tissue temperatures from absorbed energy during exposure and do not cover possible health or bio-effects related to long-term low-level exposures.

The city centre of Melbourne, which exhibited the highest exposure, is a central business district with strong cell phone network coverage (OpenSignal, 2015; Radio Frequency National Site Archive, 2015). Furthermore, other high exposure microenvironments in Australia were either characterised with densely sited mobile phone towers [e.g. railway station, residential outdoor (urban)] or use of public transport (e.g. bus and train). Except for bicycle (urban), the lowest exposure contributing microenvironments in Australia were either located in rural and suburban regions of Melbourne [car (urban/suburban), residential outdoor (rural/suburban)], or were indoor microenvironments [office indoor and residential indoor (urban)]. The rural and suburban microenvironments in Melbourne were located about 20 km northeast of Melbourne's city centre with relatively fewer mobile phone towers (OpenSignal, 2015; Radio Frequency National Site Archive, 2015) and lower population density.

Of all microenvironments in Belgium, the tram station and bicycle provided the highest exposures, mainly due to denser base stations. During the measurements, two mobile phone towers were sited near the tram station and three mobile phone towers were situated in the subject's line-of-sight while performing the bicycle measurements. The other high exposure microenvironments, city centre, residential outdoor and park were characterised by higher mobile phone tower density and stronger network signal strength (Antenna Site Register, 2015; OpenSignal, 2015). As visualised on online databases of mobile phone base stations and signal strength, the density of base stations and signal strengths across these areas is relatively high compared to that in rural and suburban regions of Belgium (Mol). The microenvironments located in the rural and suburban regions of Mol (e.g. bicycle, residential outdoor, residential indoor, and car] provided the lowest exposure. These regions only have a few base stations, low signal strength and low population density.

In general, the exposures measured across most microenvironments in Australia were much lower than those measured across similar microenvironments in Belgium. Higher population density and building characteristics (densely sited and fewer tall buildings) may have attributed to the higher observed exposures across most of the microenvironments in Belgium (Gent) compared to those observed across the microenvironments in Australia (Melbourne). Interestingly, the city centre and train in Australia characterised higher exposures compared to those of the city centre of Gent and the train in Belgium. This is due to the fact that Melbourne city centre has many densely sited base stations and high rise buildings compared to Gent. In the case of the train in Melbourne, a train travelled within the urban regions with many people travelling on board. Whereas the train from Gent to Antwerp mostly travelled through suburban and rural regions, where the mobile phone network was expected to be weaker. Furthermore, trains in Belgium have windows with metallic coatings on them, which make them very good Faraday cages, subsequently providing low downlink exposure levels. These reasons probably explained why the train in Melbourne provided higher downlink exposure than in Gent. A rural site, mountain/forest, provided high exposure level, which could be due to its location with respect to the nearby base station, and we also observed a person making mobile phone calls when the measurements at the site were performed. The measurements in Belgium and Australia were performed during Spring and Autumn respectively. Furthermore, RF-EMF is also absorbed by the leaves of trees, which would vary according to the amount of foliage present according to different seasons of the year. Mobile phone base stations vary their broadcasting power to provide optimum signal coverage (Bolte and Eikelboom, 2012). Finally, the two countries also have some differences in terms of their natural environments and physical infrastructures, which may influence the mobile phone network in specific areas. The mobile telecommunication systems have been evolving from 2G to 3G worldwide, including in Australia and Belgium (International Telecommunication Union, 2010). The difference in mobile phone base station exposure between these two countries is therefore unlikely to be stable in time.

It was also observed that the personal exposures in urban microenvironments were much higher than those in rural and suburban microenvironments in both Australia and Belgium. Furthermore, the exposure levels across indoor microenvironments were much lower than those across the outdoor microenvironments. It is well known that microenvironments in an urban area generally provide higher GSM DL exposure compared to those located in rural or suburban areas (Bolte and Eikelboom, 2012; Joseph et al., 2010; Urbinello et al., 2014a; Vermeeren et al., 2013). Likewise, indoor microenvironments provide lower GSM DL exposure than outdoor microenvironments (Bolte and Eikelboom, 2012; Joseph et al., 2010; Urbinello et al., 2014a).

The exposure levels found in our study can be compared to those reported by previous studies conducted in Belgium and other parts of Europe (e. g. Joseph et al., 2010; Urbinello et al., 2014a, 2014b). Joseph et al. (2010) examined the combined downlink (GSM 900, GSM 1800 and UMTS 2100) personal exposure across similar microenvironments in Belgium, Switzerland, Slovenia, Hungary, and the Netherlands, and reported mean exposures for similar microenvironments such as urban outdoor, office, train, car/bus, urban residential (indoor). Similarly, Urbinello et al. (2014a, 2014b) also evaluated the combined downlink personal exposure across similar microenvironments in Gent and Brussels (Belgium) and Basel (Switzerland) – residential outdoor (central urban), residential outdoor, city centre, suburban outdoor, train, tram/metro, bus, train station and shopping centre. In general, the mean exposures reported in these studies were slightly lower than those reported in our study (mean exposure values not shown in Table 2). We need to be cautious comparing the exposure reported in our study with those reported in previous studies. The main reasons are: i) we employed an on-body calibrated exposimeter with 3 antennas while those studies used a free space calibrated, single antenna exposimeter (EME Spy) with different measurement intervals, ii) we have only measured GSM 900 MHz DL whereas these studies measured combined downlink signals of three frequency bands. Furthermore, the spatial and temporal characteristics of measurements and measured microenvironments applicable to these studies may have also differed.

Our study demonstrated that GSM 900 MHz DL signals may be highly variable in the same microenvironment on different days. Urbinello et al. (2014c) showed that the environmental exposure levels of mobile phone DL signals across the same areas demonstrated variability in exposure levels. In general, diurnal variation in mobile phone signals in human environments is possible according to spatio-temporal factors (Manassas et al., 2012; Vermeeren et al., 2013; Urbinello et al., 2014c). The true mean exposure values in the microenvironments are unknown, it is simply proposed that two measurements should get a closer estimate than one. Since the path/occupancy during the measurements were nearly identical for most of the microenvironments, it is therefore unlikely that exposure variation can be attributed only to the small potential differences in paths or occupancies in the successive measurements.

The Spearman correlations between the exposure measured with the PDE and that measured with the ExpoM-RFs for all microenvironments were high. The correlation between the exposure measured with the PDE and that measured with the ExpoM-RFs seemed to be higher in the case of the Belgian microenvironments compared to the Australian microenvironments (results not shown). This is likely because overall exposure levels in Australia were lower than in Belgium. The correlation was much stronger in stationary microenvironments compared than mobile microenvironments (transportation). This may be due to the fact that the subject was essentially stationary (seated or standing only) in the mobile microenvironments. On the other hand, the subject moved across the stationary microenvironments, allowing some averaging out of body shielding.

4.2. Calibration of the exposimeters

A median antenna aperture of the PDE worn on the body was 1.05 cm^2. This is lower than the values found in Vanveerdeghem et al. (2015) (6.6 cm^2) and Thielens et al. (2015c) (6.1 cm^2). We attribute this to the different on-body setup (3 antennas instead of four) and the different assumption on the incident polarizations. In this paper, no assumptions were made on the incident polarization, since the PDE was to be used in different microenvironments that all have their own characteristic polarization distribution. Whereas Vanveerdeghem et al. (2015) (6.6 cm^2) and Thielens et al. (2015c) used the PDE only in an urban environment and consequently a-priori assumptions could be made on incident polarizations. However, the antenna aperture is in the same order of magnitude and realistic for this type of on-body antenna (Thielens et al., 2015c; Vanveerdeghem et al., 2015). The corresponding value of the PI_{50} for antenna aperture of the PDE was 3.3 dB, which is much lower than measured in our study for the individual antennas (i.e.13.6 dB, 6.5 dB, and 6.1 dB). The value was also lower than that reported for single antennas in the same frequency band (Thielens et al., 2013, 2015c; Vanveerdeghem et al., 2015). This indicates that averaging over multiple antennas on the body reduces the variation on the antenna aperture. In Thielens et al. (2013), PI_{50} value of 4.5 dB was measured for a different set-up with three antennas on the body, which indicates that the on-body setup used in this study is closer to an isotropic antenna. An isotropic antenna allows measurements with the same intensity of signals to be performed irrespective of the measurement direction. In Thielens et al. (2015c) a setup with four antennas on the body yielded a slightly lower PI_{50} of 3.1 dB, which was to be expected since more antennas on the body leads to lower PI_{50} values.

The responses of the ExpoM-RFs indicated that the devices underestimated the incident electric field strengths by a factor of approximately 2. The PI_{50} of the geometric average of the two ExpoM-RFs was found to be lower than that of one of the individual ExpoM-RFs (i.e. ExpoM-RF 40). The responses and PI_{50} values of the ExpoM-RFs can be compared to those observed in previous studies. Bolte et al. (2011) measured responses in the GSM 900 MHz DL band between −20 dB and +3 dB were on the body, with median responses below 0 dB (a factor of 1), which agrees with our results. Thielens et al. (2015a) reported values between −10 dB and +5 dB in the same frequency band, with a median underestimation, which is in line with our calibration results. The PI_{50} value observed in our study was lower than what was found for a single exposimeter in other studies in the same frequency band of GSM 900 MHz DL. In Bolte et al. (2011), a single exposimeter (EME Spy 121) was worn on the right hip of a subject rotated over 360° under exposure in the same frequency band. PI_{50} values of 6.5 dB and 15.5 dB were measured for two orthogonal polarizations. Thielens et al. (2015a), measured PI_{50} values of 8.3 dB and 9.6 dB for an exposimeter (EME Spy 140) placed on the right and left hips, respectively. In the same study, a value of 4.6 dB was found for an average over the two exposimeters worn on both hips, which corresponds very well with the 4.2 dB observed in our study.

4.3. Strengths, limitations and implications

To our knowledge, this is the first microenvironmental exposure study to evaluate RF-EMF exposures with the use of a novel, on-body calibrated system of exposimeter, with multiple antennas. The study also provides a basis for a direct valid comparison of exposures across the microenvironments in Australia and Belgium with different geophysical, environment and weather conditions. Furthermore, this study evaluates the correlation between the PDE and the ExpoM-RFs measurements while measuring GSM 900 MHz DL personal exposure.

All the received RF-EMF signals collected in this study were above the lower measurable threshold of the PDE. This is a major strength of this study as it meant there was no issue related to measurements below the lower detection threshold, which has been noted as a major challenge in exposure assessment (Bolte and Eikelboom, 2012; Frei et al., 2009; Joseph et al., 2010; Juhász et al., 2011; Urbinello et al., 2014b). Our study employed ExpoM-RFs, which demonstrated no problem with the issue of detection threshold. Another major strength of our study is that this approach minimised the measurement uncertainties related to body shielding as the PDE consisted of three antennas, which would be expected to provide a much more accurate representation of true personal exposure with fewer measurement uncertainties.

The limitations associated with the study were: i) only GSM 900 MHz DL frequency was considered, ii) the personal exposure was measured only for few selected microenvironments, which means the exposures could not be generalised to other microenvironments, ii) not all measurements were repeated and data were not always obtained with all three antennas of the PDE, iii) each measurement duration was only 15 min.

The feasibility of the PDE system for assessing RF-EMF exposures in future epidemiological studies was demonstrated. Therefore, this study contributes towards an improved exposure assessment approach for RF-EMF epidemiological studies. However the use of an on-body calibrated exposimeter in epidemiological research may not be the most pragmatic approach, since an on-body calibration of the human subject is time intensive and costly work, which is not practicable for large number of subjects in epidemiological studies. In addition, we do not yet know how a limited number of on-body calibrations on a set of subjects can be translated into a general calibration factor valid for the whole population (potentially taking into account body types). Currently, the PDE is being expanded to other downlink frequency bands using multi-band antennas combined with RF nodes tuned to different frequency bands, in order to be able to measure exposure in different RF frequency bands simultaneously using the same approach.

5. Conclusions

An on-body calibrated PDE was employed, for the first time, to evaluate micro-environmental personal exposure to mobile phone base stations GSM 900 MHz downlink in Australia and Belgium. The study revealed that the personal exposure levels measured in Australian microenvironments were generally lower than those in the Belgian microenvironments. The personal exposures across urban microenvironments were higher than those in the rural and suburban microenvironments. Likewise, the exposure levels across the outdoor microenvironments were much higher than those across the indoor microenvironments. A majority of the second measurements in the same site provided highly varied exposures. Overall, the PDE and the ExpoM-RFs measurements demonstrated good correlation. The study confirmed that the personal exposure levels reported in our study were well below the general public reference levels.

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Appendix A

Table 1
A summary of the microenvironments, their characteristics and the associated activities of the subject.

Microenvironments	Countries	Study sites and characteristics	Activities
Residential outdoor (urban)	Australia[2]	Windsor, Melbourne; attached houses mostly up to 2 storeys, few >3–6 storey buildings	Walking through streets
	Belgium[1]	Gent-Ledeberg; attached houses mostly up to 3 storeys, busy streets, and a church	
Residential indoor (urban)	Australia[2]	Prahran townhouse, ground floor	Walking inside the different rooms of the house
Office indoor (urban)	Australia[2]	Commercial Rd, Melbourne (5th floor); a 7-storey university building, multistorey hospital buildings and academic centres, a park and residential area nearby	Sitting on the chair at the working desk, walking around the office rooms
	Belgium[2]	Gaston Crommenlaan, Gent (2nd and 3rd floor); a typical multistorey public office building	
Park (urban)	Australia[2]	Fawkner Park, South Yarra, Melbourne; a typical public park with many trees, roads surrounding the park with closely attached buildings/houses on the two sides of park, bus/tram stations nearby	Walking around the park
	Belgium[2]	Koning Albertpark, Ghent; a typical public park, roads surrounding the park with closely attached buildings/houses on the two sides of park, bus/tram stations nearby	
City centre	Australia[2]	Federation Square, Melbourne; an open city area with bus/tram station, central business district with many tall buildings, including few up to >50 storeys, Yarra river nearby	Walking around the city square
	Belgium[1]	Korenmarkt, Gent; an open city area with bus/tram station, church and other historical buildings nearby	
Library (urban)	Australia[2]	Prahran, Melbourne; a public library with 25–30 people inside, densely packed area with attached buildings/houses mostly up to 3–4 storeys	Walking inside the library, checking books, reading newspapers (standing)
	Belgium[1]	Zuid, Ghent; a public library with two levels, bus and tram station nearby, a park on its one side and city buildings around	
Shopping centre (urban)	Australia[1]	Bourke Street, Melbourne; a 2-storey shopping mall	Walking inside the mall as a customer
	Belgium[1]	Zuid, Gent; 5-storey shopping mall with an open space in the centre of the building	
Railway station (urban)	Australia[2]	Southern Cross Station, Melbourne; the largest train station in Victoria with regional railway and city metro networks (2-storey), retail stores and cafes	Standing and walking in the waiting hall of the station
	Belgium[1]	Gent-Sint-Pieters railway station; the main railway station in Gent and one of the busiest railway stations in Belgium, retail stores and cafes	
Tram station (urban)	Australia[2]	Domain Interchange, Melbourne; a typical tram station with 15–20 people around, business and public buildings nearby	Standing and walking around the tram waiting points
	Belgium[1]	Zuid station, Gent; a typical tram/bus station with 20–30 people around, buildings and shopping centres nearby	
Bicycle (urban)	Australia[2]	Commercial road–Birdwood Ave, Melbourne; park and attached houses/multistorey buildings (up to 10 levels) on the both sides of the road, trees along the roadside	Riding a bicycle around
	Belgium[1]	Gaston Crommenlaan and Zuid, Gent; roads (with a flyover), park and attached houses and multistorey buildings on the sides of the roads and park	Riding a bicycle around
Bus (urban)	Australia[2]	Alfred hospital–Cardigan street, Melbourne; the public bus plied through the area with mostly 3–4 storey houses and a few big buildings, on average 10–15 people on board	Standing and sitting on a seat located in the middle part of the bus
	Belgium[2]	Zuid–Merelbeke, and Zuid–Fratersplein, Gent; the public bus plied through the area with mostly 3–4 storey houses and few big buildings, on average 20–25 people on board	
Car (urban)	Australia[1]	Eaglemont–Eltham, Melbourne; streets with normal urban/suburban traffic and densely packed area and detached houses mostly up to 2–3 storey	Sitting on the front seat of the car
	Belgium[2]	Gaston Crommenlaan – Dampoort, and Gaston Crommenlaan- Sint-Pieters station; streets with busy traffic and densely packed areas with some tall public and commercial buildings	
Tram (urban)	Australia[2]	The Alfred hospital–Collins street, Melbourne; on average 20–25 people on board	Standing and sitting on a seat
	Belgium[1]	Jacques Eggermontstraat–Zwijnaarde, Gent; on average 15–20 people on board	
Train	Australia[2]	Flinders Street–Elsternwick, Melbourne (urban), on average 20–30 people on board	Standing, sitting on a seat
	Belgium[1]	Gent–Antwerp (urban and suburban), on average 20–30 people on board	Standing, sitting on a seat
Bicycle (rural/suburban)	Belgium[1]	Boeretang, Mol; a few scattered houses up to 3 storey, a pine tree forest and open agricultural fields, ~3 km from a small town (Mol)	Riding a bicycle around
Car (rural/suburban)	Belgium[1]	Boeretang–Mol; car ride via areas with agricultural fields, forests, and residential sites	Sitting on the front seat of the car
Residential indoor (rural/suburban)	Belgium[2]	Boeretang, Mol; a 3-storey residential quarter, a pine tree forest, agricultural fields and a canal around	Walking and sitting in the common room, kitchen, etc.
Residential outdoor (rural/suburban)	Australia[2]	Tarrawarra, Victoria; few scattered houses, agricultural fields	Walking around the area
	Belgium[2]	Boeretang, Mol; a few scattered houses, pine tree forests, a canal and agricultural fields around	
Subway station/ride (urban)	Australia[1]	Parliament–Flagstaff, Melbourne; a typical subway station with 20–30 people around and 20–25 people on the train carriage	Standing both at the station and on the metro
Mountain/forest (rural)	Australia[1]	Cathedral Range State Park, Taggerty, Victoria; forested hills, one person around	Walking along trails in forest area

1 = single measurement, 2 = repeated (second) measurement.

Appendix B

On-body calibration procedure

In step one, the E_{inc} was measured without the subject present in the fully-anechoic chamber. The measurements of E_{inc} were carried out along the axis of rotation of the platform using a NBM-550 broadband field meter (Narda, Hauppauge, NY, USA). The E_{inc} values were then averaged over the height of the subject (ICNIRP, 1998). This procedure was repeated for two orthogonal polarizations of the T_X: parallel to the axis of rotation (V-polarization) and parallel to the floor of the chamber (H-polarization).

In step two, the subject equipped with the PDE stood on the rotational platform in the far field of the T_X. Three on-body antennas (Thielens et al., 2013; Vanveerdeghem et al., 2015) were placed on the locations shown in Fig. 1a & b. The antennas used in this study were linearly polarized planar inverted F-antennas (Thielens et al., 2013; Vanveerdeghem et al., 2015). The two antennas placed on the front of the torso had orthogonal polarizations, which enabled the device to measure two orthogonal incident far-field polarizations. The antennas were connected, using a shielded SubMiniature version A cable, with RF nodes that contained a surface acoustic wave filter tuned to the 900 MHz downlink band (925–960 MHz). The SAW filter provided an out-of-band isolation of more than 23 dB (Vanveerdeghem et al., 2015). The cables shown in Fig. 1 were used to connect the RF nodes with a battery which was worn on the hips of the subject and did not influence the RF performance of the PDE. The cables and the battery were included in the on-body calibration. The subject was rotated over 360° in azimuthal direction from a constant electric field (E_{inc}), which was V-polarized during the first rotation and then H-polarized. This rotation represented the unknown orientation of the subject in an exposure situation (Thielens et al., 2013). During the rotation the antennas recorded received powers (P_r) on the body. These received powers depend on the rotational angle, due to shadowing of the body (Thielens et al., 2013, 2015b; Vanveerdeghem et al., 2015), and the polarization of the T_X.

The received powers (P_r) were related to the incident electric field strength (E_{inc}) through the effective antenna aperture (AA):

$$AA = \frac{377 \times P_r}{{E_{inc}}^2}$$

Since P_r depends on the angle of incidence, the AA will have a distribution. In determining its distribution, we assumed both polarizations to be equally likely to occur. The distribution of AA was characterised by its median value [p_{50} (AA)] and 50% prediction interval PI_{50} (with p_{25} (AA) and p_{75} (AA), the 25th and 75th percentile of the distribution of AA):

$$PI_{50} = \frac{p_{75}(AA)}{p_{25}(AA)}$$

A perfect exposimeter, i.e. an antenna with a constant AA, will have a $PI_{50} = 1$, so a value close to one is desirable.

During measurements, the incident field strengths can be estimated from the measured received powers (P_r) using this antenna aperture. In this study, we estimated the incident field strength (E_{inc}), using the median AA [p_{50} (AA)]:

$$E_{inc} = \sqrt{\frac{377 \times P_r}{p_{50}(AA)}}$$

In step three, two ExpoM-RFs were employed in the on-body calibration process to determine the relationship between the incident electric field strengths (E_{inc}) and the electric field strengths on the body (E_{body}). These devices are meant to measure E_{inc}, but since they were worn on the body during measurements, they registered E_{body} instead (Bolte et al., 2011; Thielens et al., 2015a). The human subject equipped with the ExpoM-RFs (as shown in Fig. 1c) stood on the rotational platform in the far field of the T_X. Two ExpoM-RFs were placed to the body (Thielens et al., 2013; Vanveerdeghem et al., 2015) on the locations of each hip. The subject was rotated over 360° in azimuthal direction, while being exposed to a constant electric field (E_{inc}), which is first V-polarized and then H-polarized. This rotation represented the unknown orientation of the subject in an exposure situation (Thielens et al., 2013). During the rotation, the ExpoM-RFs recorded the electric fields on the body (E_{body}). These on-body fields and received powers depend on the rotational angle, due to shadowing of the body (Thielens et al., 2013, 2015b; Vanveerdeghem et al., 2015), and the polarization of the T_X. The E_{body} values were not the same as the incident values (E_{inc}) (Thielens et al., 2015a), therefore, the response (R) of the ExpoM-RFs was evaluated as:

$$R = \frac{E_{body}}{E_{inc}}$$

$R > 1$ and < 1 indicated an overestimation or an underestimation respectively. R is not a constant and will have a certain distribution (Thielens et al., 2015a) for each of the two measured orientations of the T_X. In the processing of the results, we made no a-priori assumptions on the incident polarization of the realistic fields and thus assumed each polarization to be equally likely. Therefore, all measured R values were combined in one distribution characterised by its median value (p50(R)) and 50% prediction interval (PI_{50}):

$$PI_{50} = \frac{p_{75}(R)}{p_{25}(R)}$$

with $p75(R)$ and $p25(R)$ indicating the 75th and 25th percentiles of R, respectively. During measurements, the incident field strengths can be estimated from the measured electric field strengths (E_{meas}) using this response. We estimated the incident field strength ($\mathrm{E_{inc}}$), using the median ($p50(R)$):

$$\mathrm{E_{inc}} = \frac{\mathrm{E_{meas}}}{\mathrm{p_{50}(R)}}$$

with E_{meas} the geometric averaged measured electric field strength.

The used calibration procedure is valid for far-field exposure, but might not be suitable for sources close to the body, such as mobile phones or personal devices, which might cause a large variation of the electric field strength on the body. The calibration procedure can be used in this study, where far-field, downlink exposure around 900 MHz is studied.

References

ACMA communications report, 2014. Communications reports 2013–14. http://www.acma.gov.au/~/media/Research%20and%20Analysis/Publication/Comms%20Report%202013%2014/PDF/Communications%20report%201314_LOW-RES%20FOR%20WEB%20pdf.pdf (Accessed on 12.09.2015).

ACMA paper, 2015. Beyond 2020 — A spectrum management strategy to address the growth in mobile broadband capacity. Discussion paper. http://www.acma.gov.au/Industry/Spectrum/Spectrum-planning/About-spectrum-planning/acma-focuses-on-future-of-mobile-broadband-spectrum (Accessed on 12.09.2015).

Antenna Site Register, 2015. http://www.sites.bipt.be/index.php?language=EN. Accessed on 30.09.2015.

Bhatt, C.R., Redmayne, M., Abramson, M., Benke, G., 2016. Instruments to assess and measure personal and environmental radiofrequency-electromagnetic field exposures. Australas. Phys. Eng. Sci. Med. 39, 29–42.

Bolte, J.F.B., Eikelboom, T., 2012. Personal radiofrequency electromagnetic field measurements in the Netherlands: Exposure level and variability for everyday activities, times of day and types of area. Environ. Int. 48, 133–142.

Bolte, J.F., van der Zande, G., Kamer, J., 2011. Calibration and uncertainties in personal exposure measurements of radiofrequency electromagnetic fields. Bioelectromagnetics 32, 652–663.

Dürrenberger, G., Fröhlich, J., Röösli, M., Mattsson, M.O., 2014. EMF monitoring—concepts, activities, gaps and options. Int. J. Environ. Res. Public Health 11, 9460–9479.

Frei, P., Mohler, E., Neubauer, G., Theis, G., Burgi, A., Frohlich, J., Braun-Fahrlander, C., Bolte, J., Egger, M., Röösli, M., 2009. Temporal and spatial variability of personal exposure to radio frequency electromagnetic fields. Environ. Res. 109, 779–785.

Gajšek, P., Ravazzani, P., Wiart, J., Grellier, J., Samaras, T., Thuróczy, G., 2015. Electromagnetic field exposure assessment in Europe radiofrequency fields (10 MHz–6 GHz). J. Expo. Sci. Environ. Epidemiol. 25, 37–44.

Henderson, S., Bangay, M., 2006. Survey of RF exposure levels from mobile telephone base stations in Australia. Bioelectromagnetics 27, 73–76.

ICNIRP, 1998. The International Commission on Non-ionizing Radiation Protection. Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 300 GHz). Health Phys. 74 (4), 494–522.

International Telecommunication Union, 2010. The evolution to 3G mobile — status report. https://www.itu.int/itunews/issue/2003/06/thirdgeneration.html (Accessed on 27.02.2016).

Iskra, S., McKenzie, R.J., Cosic, I., 2011. Monte Carlo simulations of the electric field close to the body in realistic environments for application in personal radiofrequency dosimetry. Radiat. Prot. Dosim. 147, 517–527.

Joseph, W., Verloock, L., 2010. Influence on mobile phone traffic on base station exposure of the general public. Health Phys. 99 (5), 631–638.

Joseph, W., Frei, P., Roösli, M., Thuróczy, G., Gajsek, P., Trcek, T., Bolte, J., Vermeeren, G., Mohler, E., Juhász, P., Finta, V., Martens, L., 2010. Comparison of personal radio frequency electromagnetic field exposure in different urban areas across Europe. Environ. Res. 110, 658–663.

Juhász, P., Bakos, J., Nagy, N., Jánossy, G., Finta, V., Thuróczy, G., 2011. RF personal exposimetry on employees of elementary schools, kindergartens and day nurseries as a proxy for child exposures. Prog. Biophys. Mol. Biol. 107, 449–455.

Kim, K., Kim, H.-J., Song, D.J., Cho, Y.M., Choi, J.W., 2014. Risk perception and public concerns of electromagnetic waves from cellular phones in Korea. Bioelectromagnetics 35 (4), 235–244.

Manassas, A., Boursianis, A., Samaras, T., Sahalos, J.N., 2012. Continuous electromagnetic radiation monitoring in the environment: analysis of the results in Greece. Radiat. Prot. Dosim. 151 (3), 437–442.

Mann, S., 2010. Assessing personal exposures to environmental radiofrequency electromagnetic fields. C. R. Phys. 11, 541–555.

Neubauer, G., Cecil, S., Giczi, W., Petric, B., Preiner, P., Fröhlich, J., Röösli, M., 2010. The association between exposure determined by radiofrequency personal exposimeters and human exposure: a simulation study. Bioelectromagnetics 31, 535–545.

OpenSignal, 2015. http://opensignal.com (Accessed on 17.08.2015).

Radiation Protection Standard, 2002. Maximum Exposure Levels to Radiofrequency Fields — 3 kHz to 300 GHz. Radiation Protection Series Publication No. 3. the Australian Radiation Protection and Nuclear Safety Agency. pp. 1–128.

Radio Frequency National Site Archive, 2015. http://www.rfnsa.com.au/nsa/index.cgi?type=logout (Accessed on 17.08.2015).

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, R.C., Poulsen, A.H., Radon, K., Schuz, J., Thuroczy, G., Viel, J.F., Vrijheid, M., 2010. Conduct of a personal radiofrequency electromagnetic field measurement study: proposed study protocol. Environ. Health 9 (23), 1–14.

Rowley, J.T., Joyner, K.H., 2012. Comparative international analysis of radiofrequency exposure surveys of mobile communication radio base stations. J. Expo. Sci. Environ. Epidemiol. 22, 304–315.

Thielens, A., De Clercq, H., Agneessens, S., Lecoutere, J., Verloock, L., Declercq, F., Vermeeren, G., Tanghe, E., Rogier, H., Puers, R., 2013. Personal distributed exposimeter for radio frequency exposure assessment in real environments. Bioelectromagnetics 34, 563–567.

Thielens, A., Agneessens, S., Verloock, L., Tanghe, E., Rogier, H., Martens, L., Joseph, W., 2015a. On-body calibration and processing for a combination of two radio-frequency personal exposimeters. Radiat. Prot. Dosim. 163, 58–69.

Thielens, A., Agneessens, S., De Clercq, H., Lecoutere, J., Verloock, L., Tanghe, E., Aerts, S., Puers, R., Rogier, H., Martens, L., Joseph, W., 2015b. On-body calibration and measurements using a personal, distributed exposimeter for Wireless Fidelity. Health Phys. 108 (4), 407–418.

Thielens, A., Vanveerdeghem, P., Agneessens, S., Van Torre, P., Vermeeren, G., Rogier, H., Martens, L., Joseph, W., 2015c. Whole-Body averaged specific Absorption rate stimation using a personal distributed exposimeter. IEEE AWPL 14, 1534–1537.

Tjong, L., Grzechnik, M., Karipidis, K., Tinker, R., 2015. Communicating with the Public – Recent ARPANSA Updates. Proc the 40th Australasian Radiation Protection Society Conference, Canberra, Australia, pp. 6–9 (October 2015).

Urbinello, D., Joseph, W., Verloock, L., Martens, L., Röösli, M., 2014a. Temporal trends of radio-frequency electromagnetic field (RF-EMF) exposure in everyday environments across European cities. Environ. Res. 134, 134–142.

Urbinello, D., Joseph, W., Huss, A., Verloock, L., Beekhuizen, J., Vermeulen, R., Martens, L., Roosli, M., 2014b. Radio-frequency electromagnetic field (RF-EMF) exposure levels in different European outdoor urban environments in comparison with regulatory limits. Environ. Int. 68, 49–54.

Urbinello, D., Huss, A., Beekhuizen, J., Vermeulen, R., Röösli, M., 2014c. Use of portable exposure meters for comparing mobile phone base station radiation in different types of areas in the cities of Basel and Amsterdam. Sci. Total Environ. 468–469, 1028–1033.

van Deventer, E., van Rongen, E., Saunders, R., 2011. WHO research agenda for radiofrequency fields. Bioelectromagnetics 32, 417–421.

Vanveerdeghem, P., Vantorre, P., Thielens, A., Knockaert, J., Joseph, W., Rogier, H., 2015. Compact personal distributed wearable exposimeter. IEEE Sensors J. 15 (8), 4393–4401.

Vermeeren, G., Markakis, I., Goeminne, F., Samaras, T., Martens, L., Joseph, W., 2013. Spatial and temporal RF electromagnetic field exposure of children and adults in indoor micro environments in Belgium and Greece. Prog. Biophys. Mol. Biol. 113, 254–263.

Wiedemann, P.M., Boerner, F.U., Repacholi, M.H., 2014. Do people understand IARC's 2B categorization of RF fields from cell phones? Bioelectromagnetics 35, 373–378.

Chapter 4. Assessment of personal exposure from RF-EMFs

Overview

As human RF-EMF exposure comprises the exposures from a number of frequency bands, it becomes important to identify and quantify the key sources and their corresponding exposure levels in human environments. Unlike previous chapter, this chapter discusses and summarises the exposure measured for different sources of RF-EMF such as FM radio/television, mobile phone base stations (various frequencies of 2G, 3G and 4G) and Wi-Fi across various microenvironments in Melbourne, Australia, and in/around Ghent, Belgium.

This work also employed a new approach to RF-EMF exposure assessment – the concurrent use of two on-body calibrated exposimeters. Therefore the work not only provides more accurate exposure assessment results by minimising body-shielding related measurement uncertainties but also explores the feasibility of such approach (88, 89, 91). The chapter also compares the exposure levels measured for one site in each of several selected microenvironments in the two countries.

The paper concluded that it was feasible to employ two exposimeters concurrently to estimate personal exposure minimizing the consequences of body shielding. Therefore, exposure assessment with the use of two on-body calibrated exposimeters has benefits over the use of a single non-on-body calibrated exposimeter and hence is recommended, if possible. Mobile phone Base down link exposures contributed the largest share to total exposures. Of 17 microenvironments compared, nine of them provided lower exposure levels in Melbourne (Australia) than the corresponding microenvironments in Ghent (Belgium). The personal exposures across urban microenvironments were higher than those in rural and suburban microenvironments. Similarly, exposure levels found across outdoor microenvironments were higher than indoors.

Declaration for Thesis Chapter 4

Manuscript: **Bhatt CR,** Thielens A, Billah B, Redmayne M, Abramson MJ, Sim MR, Vermeulen R, Martens L, Joseph W, Benke G. Assessment of personal exposure from radiofrequency- electromagnetic fields in Australia and Belgium using on-body calibrated exposimeters. *Environmental Research* 2016, 151: 547–563.

Declaration by candidate

In the case of Chapter 4, the nature and extent of my contribution to the work was the following:

Nature of contribution	**Extent of contribution (%)**
Study design, data collection, data analysis, manuscript development and preparation	80%

The following co-authors contributed to the work. Where co-authors are students at Monash University, the extent of their contribution in percentage terms is stated:

Names	Nature of contribution
Arno Thielens	Data collection, data analysis and interpretation, development of manuscript, manuscript editing and revision of submitted manuscript
Baki Billah	Data analysis and interpretation, development of manuscript and manuscript editing
Mary Redmayne	Data interpretation, manuscript editing, revision of submitted manuscript, and supervision
Michael J. Abramson	Data interpretation, manuscript editing, revision of submitted manuscript, and supervision

Malcolm R. Sim	Study concept and design, study funding, data interpretation, manuscript editing and revision of submitted manuscript
Roel Vermeulen	Study concept and design, study funding, data interpretation, manuscript editing and revision of submitted manuscript
Luc Martens	Data interpretation, manuscript editing and revision of submitted manuscript
Wout Joseph	Data collection, data analysis and interpretation, manuscript editing and revision of submitted manuscript
Geza Benke	Study concept and design, study funding, data interpretation, manuscript editing, revision of submitted manuscript and supervision

The undersigned hereby certify that the above declaration correctly reflects the nature and extent of the candidate's and co-authors' contribution to this work.

Candidate's Signature	[redacted]	Date 28/04/2017

Main Supervisor's Signature	[redacted]	Date 28/04/2017

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Assessment of personal exposure from radiofrequency-electromagnetic fields in Australia and Belgium using on-body calibrated exposimeters

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ABSTRACT

The purposes of this study were: i) to demonstrate the assessment of personal exposure from various RF-EMF sources across different microenvironments in Australia and Belgium, with two *on-body* calibrated exposimeters, in contrast to earlier studies which employed single, non-on-body calibrated exposimeters; ii) to systematically evaluate the performance of the exposimeters using (on-body) calibration and cross-talk measurements; and iii) to compare the exposure levels measured for one site in each of several selected microenvironments in the two countries. A human subject took part in an on-body calibration of the exposimeter in an anechoic chamber. The same subject collected data on personal exposures across 38 microenvironments (19 in each country) situated in urban, suburban and rural regions. Median personal RF-EMF exposures were estimated: i) of all microenvironments, and ii) across each microenvironment, in two countries. The exposures were then compared across similar microenvironments in two countries (17 in each country).

The three highest median total exposure levels were: city center (4.33 V/m), residential outdoor (urban) (0.75 V/m), and a park (0.75 V/m) [Australia]; and a tram station (1.95 V/m), city center (0.95 V/m), and a park (0.90 V/m) [Belgium]. The exposures across nine microenvironments in Melbourne, Australia were lower than the exposures across corresponding microenvironments in Ghent, Belgium ($p < 0.05$). The personal exposures across urban microenvironments were higher than those for rural or suburban microenvironments. Similarly, the exposure levels across outdoor microenvironments were higher than those for indoor microenvironments.

1. Introduction

Concern regarding potential health and biological effects in humans from made sources of radiofrequency-electromagnetic fields (RF-EMFs) exposure has increased in the last decade. The International Agency for Research on Cancer has listed RF-EMF as a possible human carcinogen (Group 2B) (Baan et al., 2011). Furthermore, the World Health Organization emphasized the need of evaluation of personal exposures, from multiple RF-EMF sources for human epidemiological studies using objective measurements (van Deventer et al., 2011).

Personal RF-EMF exposures from far-field RF-EMF sources, such as those from mobile phone base stations, TV/radio signals, Wireless-Fidelity (Wi-Fi), have been evaluated employing exposimeters (Dürrenberger et al., 2014; Joseph et al., 2010; Röösli et al., 2010; Sagar et al., 2016; Urbinello et al., 2014a). These studies used a single exposimeter worn by human subjects to

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measure whole body RF-EMF exposure, but the exposimeters were not calibrated on body. In fact the use of a single exposimeter, may result in measurement uncertainties, particularly those related to the body shielding effects, residual calibration, and the frequency response of the measurement device (Bolte et al., 2011; Gajšek et al., 2015; Iskra et al., 2010, 2011b; Mann, 2010; Neubauer et al., 2010). Iskra et al. (2010, 2011) suggested that the use of two exposimeters placed on different locations on the body may minimize the measurement uncertainties. It has also been demonstrated that wearing two *on-body* calibrated exposimeters, one on each hip, provided more accurate personal exposure measurements with a lower measurement uncertainty (Thielens et al., 2015a).

Studies investigating personal exposure levels from various far-field RF-EMF sources have been mainly conducted in European countries (Bolte and Eikelboom, 2012; Frei et al., 2009; Gajšek et al., 2015; Joseph et al., 2010; Sagar et al., 2016; Urbinello et al., 2014b, 2014c; Vermeeren et al., 2013). There is a paucity of similar comparable data from elsewhere, including Australia. Therefore, a comparative study employing similar study protocols, involving countries outside Europe would be informative to the rest of the world. Only limited information has been reported on environmental exposure levels from mobile phone base stations and other RF-EMF sources in Australia (Henderson et al., 2014; Henderson and Bangay, 2006; Rowley and Joyner, 2012). Furthermore, we have recently published personal exposure data from 900 MHz mobile phone base station downlink in Australia and Belgium (Bhatt et al., 2016a).

The aims of this study were: i) to demonstrate the assessment of personal exposure from various RF-EMF sources across different microenvironments in Australia and Belgium, with two *on-body* calibrated exposimeters, in contrast to earlier studies which employed single, non-on-body calibrated exposimeters; ii) to systematically evaluate the performance of the exposimeters using (on-body) calibration and cross-talk measurements; and iii) to compare the exposure levels measured for one site in each of several selected microenvironments in the two countries.

2. Materials and methods

2.1. Study areas

The study was carried out in urban, suburban, and rural sites in Australia and Belgium. The microenviromental personal measurements were performed on a single person (CRB) during 7th April–8th May and 27th March–6th April 2015, respectively. The study areas in Australia mainly covered the urban and suburban regions of Greater Melbourne, and a rural site (Cathedral Range State Park). Similarly, urban and suburban regions of Ghent and rural regions of Mol in the Flemish region of Belgium were included in the study. A region was considered to be urban when the population density was >400 people per square kilometre (Joseph et al., 2010).

A total of 38 microenvironments (Table A1, Appendix A), 19 each in Australia and in Belgium, were selected to evaluate personal exposures. Of them, the 34 matched microenvironments (17 each in each country) were: residential outdoor (urban), residential indoor (urban), office indoor (urban), park (urban), city center, library (urban), shopping center (urban), train station (urban), tram station (urban), bicycle (urban), bus (urban), car (rural/suburban), tram (urban), train, residential outdoor (rural/suburban), residential indoor (rural/suburban), and airport. In addition, subway station/ride (urban), mountain/forest (rural) in Australia, and bicycle (rural/suburban) and car (urban/suburban) in Belgium were also measured. These microenvironments have been described more fully in our previous paper (Bhatt et al., 2016a), and were similar to those of other studies (Bolte and Eikelboom, 2012; Frei et al., 2009; Joseph et al., 2010; Röösli et al., 2010; Urbinello et al., 2014a, 2014b). We also evaluated the indoor exposures in airports of both countries, Tullamarine International Airport, Melbourne, and Brussels International Airport, Brussels.

The microenvironments were primarily of two types: stationary or mobile. The stationary microenvironments remained fixed while the subject moved around in the microenvironment, whereas the mobile microenvironments moved around during the data collection, whilst the subject essentially remained stationary. The mobile microenvironments included bus, train, tram, car and bicycle, whereas stationary microenvironments included the rest, except for subway station and ride, which was a mixed microenvironment (Bhatt et al., 2016a).

2.2. Calibration procedure

The procedure involved an on-body calibration of the ExpoM-RF 64 for 15 frequency bands (in contrast to previous studies where no on-body calibration was included). The frequency bands calibrated were Digital Video Broadcasting-Terrestrial (DVB-T), 800 MHz downlink (DL) and uplink (UL), 900 MHz UL and DL, 1800 MHz UL and DL, Digital Enhanced Cordless Telecommunications (DECT), 1900 MHz UL and 2100 MHz DL, Industrial, Scientific and Medical (ISM) 2.4 GHz , 2600 MHz UL and DL, Worldwide Interoperability for Microwave Access (WiMax) 3.5 GHz and ISM 5.8 GHz. The central frequency levels calibrated were: 630 MHz (DVB-T), 806 MHz (DL), 847 MHz (UL), 897.5 MHz (900UL), 942.5 MHz (900 DL), 1747.5 MHz (1800 UL), 1842.5 MHz (1800 DL), 1890 MHz (DECT), 1950 MHz (UL), 2140 MHz (DL), 2442.5 MHz (ISM 2.4 GHz), 2535 MHz (2600 UL), 2655 MHz (2600 DL), 3500 MHz (WiMax 3.5 GHz) and 5512.5 MHz (ISM 5.8 GHz). Table B1 lists the different studied frequency bands and their frequency ranges. The personal exposure measured in this study should be interpreted as being frequency-band-specific and not attributed to a certain communication technology. The ExpoM-RF 40 was calibrated only for 900 DL MHz band. The FM radio band was not calibrated since the anechoic chamber used for the calibrations did not provide sufficient damping in this frequency band. We assumed that ExpoM-RF 40 would yield the same calibration responses as those of ExpoM-RF 64.

The ExpoM-RFs measure the incident frequency-band-specific electric field strengths (E_{inc}). The exposimeter(s), when worn on the body during measurements, register the electric field strengths on the body (E_{body}) (Bolte et al., 2011; Thielens et al., 2015a). Therefore, on-body calibration measurements are required in order to assess the relationship between E_{inc} and E_{body}. The subject (a 35-year-old male; height 163 cm and weight 60 kg) participated in the on-body calibration in order to perform the subsequent field measurements (Fig. 1a). The on-body calibration procedure is discussed in detail elsewhere (Bhatt et al., 2016a). The calibration procedure was executed in a fully anechoic chamber following the procedure described in Thielens et al. (2015a); Bhatt et al. (2016a) (see also Appendix B).

2.3. Exposure assessment

Exposimeters were simultaneously employed in data collection across the microenvironments. Using traveler's money belts, the ExpoM-RF 64 and the ExpoM-RF 40 were attached to the left and right sides of the subject's hips (Fig. 1b). Both ExpoM-RFs were switched on and switched off simultaneously to synchronize the start and the end of the measurements. The root mean square (RMS) electric field strengths measured by the ExpoM RFs have been denoted as (E_{rms}), in V/m. The lower limits of detection (LOD)

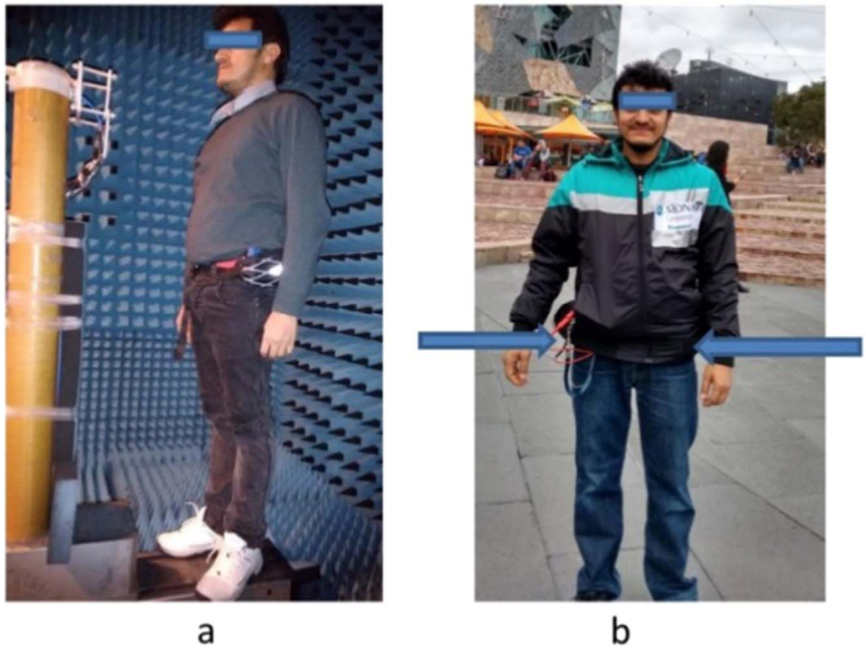

Fig. 1. The subject performing an on-body calibration of the ExpoM-RFs 64 in Ghent (a), and exposure measurement at a site in Melbourne using the on-body calibrated exposimeters (b) [arrows showing the locations of the ExpoM-RFs].

for each band of the ExpoM- RFs are: 20 mV/m (FM radio), 50 mV/m (ISM 5.8 GHz), 3 mV/m (2600 UL, DL and WiMax), and 5 mV/m (for the remaining frequencies). The upper LOD is 6 V/m in all frequency bands. The detection range of the ExpoM-RFs, with on-body calibration, is the value listed above, divided by the corresponding on-body response in the respective frequency bands. A light jacket worn by the subject covered both exposimeters while performing the measurements (Fig. 1b). The subject did not have any metal objects attached to his body during data collection.

All measurements were performed during the daytime (9:45 am–6:00 pm) or evening (6:00 pm–11:00 pm) on weekdays, except those of residential indoor and residential outdoor (rural/suburban) in Belgium, which were performed during the weekends (2:30–2:45 pm and 11:00–11:15 pm respectively). Each measurement duration was 15 min per microenvironment. A similar measurement duration were employed in the personal exposure monitoring by Urbinello et al., (2014a, 2014b). A smartphone watch, in flight mode, was used to monitor measurement time. The measurement intervals for the ExpoM-RFs were chosen to be 3 s (Bhatt et al., 2016a). Two ExpoM-RFs collected a total of 600 samples (300 each) per measurement for each microenvironment. Information on activities undertaken during data collection and descriptions of the microenvironments were recorded in a diary.

Twenty three microenvironmental measurements (13 in Australia and 10 in Belgium) were performed twice to evaluate exposure variability during the first and second measurements. We attempted to obtain as much spatio-temporal matching as possible for the repeated microenvironments. Spatial matching of the stationary microenvironmental measurements was ensured by walking across the same area/route and towards the same direction. However, in the case of city center (Belgium), the measurements were performed across the same urban area, but involved walking along a different route. For the mobile microenvironments, the spatial matching was accomplished by sitting/standing at the same spot/around the same positions with respect to window and carriage dimension. All mobile microenvironment measurements, except for car (urban) and bus (urban) in Belgium, were performed on exactly the same routes. The temporal matching, for most of the measurements, was ensured by performing the measurements (1st and 2nd) at similar times of the day, such as morning, evening or night.

2.4. Data processing and statistical analysis

The analysis commenced with an assessment of the censored exposure data (E_{rms}) falling below the lower detection limit (LODs) in the respective frequency bands for each microenvironment. A Shapiro-Wilk test was performed on the untransformed and log-transformed data to evaluate normality. Furthermore, visual inspection of histograms and the normal Q-Q plots was also carried out.

We used the substitution approach in order to estimate summary statistics from the measured data. This is an accepted method in the science of environmental exposure assessment (Hewett & Ganser, 2010). All left censored data (i.e. the data below LODs) were replaced with their frequency-specific respective values of LOD/$\sqrt{2}$ (Ganser and Hewett, 2010; Hewett and Ganser, 2007). In ISM 5.8 GHz band (of the ExpoM-RF 64 data), numerous values < LOD (non-zero) and zero values were recorded. We replaced only the non-zero values < LOD with LOD/$\sqrt{2}$. The ExpoM-RF 64 measurements < 20 mV/m in the ISM 5.8 GHz band were automatically set to zero as those values were most likely the result of crosstalk. For the ISM 5.8 GHz data of the ExpoM-RF 40, we set all values < 20 mV/m as zero and all the non-zero values < LOD with LOD/$\sqrt{2}$. The values below LODs of 2600 MHz DL and UL, and WiMax 3.5 GHz bands were replaced with zeros for the measurements of the microenvironments that were situated in the areas not covered by these networks (Radio Frequency National Site Archive, 2016). All 2600 MHz (DL and UL) data of the microenvironments in Belgium, and those of residential outdoor and residential indoor (rural/suburban) in Australia were set to zero. In addition, the data of ISM 5.8 GHz for the latter microenvironments in Australia, and those of WiMax 3.5 for the microenvironments located in rural/suburban regions of Belgium were also set to zero. Similarly, the WiMax 3.5 GHz and ISM 5.8 data of car (rural/suburban) in Australia was set to zero. In the case of mountain/forest (rural) in Australia, the data below the LODs of 900 MHz DL,

Table 1
The results of the on-body calibration of ExpoM-RF 64 attached to the left lateral hip of the subject as shown in Fig. 1.

Frequency bands	ExpoM-RF 64		Geometric mean response (two ExpoM-RFs)	
	R	PI_{50}	R_{gm}	PI_{50}
DVB-T (470–790 MHz)	0.48±0.004	8.6±0.032	0.46 ±0.002	4.9 ±0.047
800 UL (832–862 MHz)	0.58±0.004	7.3±0.062	0.54 ±0.002	2.2±0.030
800 DL (791–821 MHz)	0.47±0.002	7.3±0.021	0.46±0.001	2.1±0.006
900 UL (880–915 MHz)	0.53±0.001	6.3±0.043	0.50±0.001	1.8±0.018
900 DL (925–960 MHz)	0.44±0.0005	7.8±0.049	0.41±0.0006	1.3±0.011
1800 UL (1710–1785 MHz)	0.55 ±0.003	9.8±0.034	0.47±0.001	2.9±0.026
1800 DL (1805–1880 MHz)	0.43 ±0.002	7.9±0.060	0.40±0.002	5.1±0.020
DECT (1880–1900 MHz)	0.49±0.001	9.0±0.074	0.46 ±0.001	3.4 ±0.014
1900 UL (1920–1980 MHz)	0.73 ±0.002	7.8±0.056	0.62 ±0.001	6.4±0.009
2100 DL (2110–2170 MHz)	0.72±0.0005	8.7±0.056	0.57±0.0005	6.2 ±0.013
ISM 2.4 (2400–2485 MHz)	0.99 ±0.004	10 ±0.019	0.99±0.0008	3.1 ±0.056
2600 UL (2500–2570 MHz)	1.3±0.004	10 ±0.043	0.91±0.0004	7.2 ±0.020
2600 DL (2620–2690 MHz)	1.1 ±0.002	12 ±0.033	0.71 ±0.001	8.2 ±0.038
WiMAX 3.5 (3400–3600 MHz)	0.89 ±0.001	8.9±0.046	0.64±0.0006	4.7 ±0.014
ISM 5.8 (5150–5875 MHz)	3.1 ±0.005	8.4±0.051	2.6 ±0.012	5.7 ±0.032

DVB-T: Digital Video Broadcasting–Terrestrial, DL: Downlink, DECT: Digital Enhanced Cordless Telecommunications, ISM: Industrial, Scientific and Medical UL: Uplink, WiMAX: Worldwide Interoperability for Microwave Access, R: response (E_{body}/E_{inc}), PI_{50}: 50% prediction interval (in dB), R_{gm}: geometric mean response of two ExpoM-RFs

900 MHz UL, DVB-T, and FM Radio were substituted by their respective LOD/$\sqrt{2}$, whereas all data for the remaining bands were set to zero.

Geometric means of the electric field signals (E_{rms}) measured with two ExpoM-RFs were calculated within the selected sample intervals using the formula; *Geometric mean*=$(E_{ExpoM\text{-}RF40} \times E_{ExpoM\text{-}RF64})^{1/2}/R_{gm}$ (Bhatt et al., 2016a), where R_{gm} is the geometric mean response of two ExpoM-RFs (see Table 1). As Table 1 demonstrates the geometric averaging leads to a lower prediction interval for the measured E_{rms} values. Neubauer et al. (2008) suggested that frequency-specific calibration factor(s) should be applied while estimating RF-EMF exposures, because RF-EMF exposures close to the human body are otherwise underestimated, which depends on the dimension of the human body, positions of the body-worn exposimeter(s) and frequency bands. We have not reported the summary statistics for individual exposures measured by the ExpoM-RF. However, the frequency-specific estimated median exposures provided by the individual ExpoM-RFs across all microenvironments of each country were used to evaluate the correlation between ExpoM-RF 40 and ExpoM-RF 64. The median exposure values obtained for 19 microenvironments with ExpoM-RF 64 (n=19) and ExpoM-RF 40 (n=19) per frequency band in both countries were used to perform country-specific Spearman's rank correlation analysis. Furthermore, we also used median exposure levels measured with the ExpoM-RF 64 (without taking on-body calibration factors into account) across the 19 microenvironments in each country to compare the levels to those obtained with the concurrent use of the ExpoM-RF 64 and the ExpoM-RF 40. This would allow us to have a comparison between the exposure levels obtained with the use of a single non-on-body calibrated exposimeter (such as most personal exposimetry studies) and those obtained with the use of two on-body calibrated exposimeters (current study).

Summary statistics (mean, median, 25th, 75th and 95th percentiles) of personal exposure across the measured bands were then calculated for all microenvironments in Australia and Belgium.

The total and frequency-specific median exposures across all measured microenvironments in both countries were obtained from the distributions of medians of the total and frequency-specific RF-EMF exposures, respectively. Furthermore, the statistics of personal exposure for each microenvironment were also calculated in terms of the four exposure categories: i) total exposure, which was equal to the square root sum of the 16 bands $\left(E^2_{\text{rms-FM}} + E^2_{\text{rms-DVB-T}} + E^2_{\text{rms-800 UL}} + E^2_{\text{rms-800 DL}} + E^2_{\text{rms-900 UL}} + E^2_{\text{rms-900 DL}} + E^2_{\text{rms-1800 UL}} + E^2_{\text{rms-1800 DL}} + E^2_{\text{rms-DECT}} + E^2_{\text{rms-2100 UL}} + E^2_{\text{rms-2100 DL}} + E^2_{\text{rms-ISM 2.4}} + E^2_{\text{rms-2600 UL}} + E^2_{\text{rms-2600 DL}} + E^2_{\text{rms-WiMAX 3.5}} + E^2_{\text{rms-ISM 5.8}}\right)$; ii) mobile phone base station DLs exposure, the square root sum of all DL bands $\left(E^2_{\text{rms-800 DL}} + E^2_{\text{rms-900 DL}} + E^2_{\text{rms-1800 DL}} + E^2_{\text{rms-2100 DL}} + E^2_{\text{rms-2600 DL}}\right)$; iii) mobile phone base station UL exposure, the square root sum of all UL bands $\left(E^2_{\text{rms-800 UL}} + E^2_{\text{rms-900 UL}} + E^2_{\text{rms-1800 UL}} + E^2_{\text{rms-1900 UL}} + E^2_{\text{rms-2600 UL}}\right)$, and iv) broadcast exposure, the square root sum of FM radio and DVB-T bands $\left(E^2_{\text{rms-FM}} + E^2_{\text{rms-DVB-T}}\right)$. The total personal exposures were compared across 34 similar microenvironments (17 in each country). Four microenvironments excluded from the comparison were: subway station/ride (urban), mountain/forest (rural) in Australia, and bicycle (rural/suburban), and car (rural/suburban) in Belgium. These were excluded because comparable corresponding microenvironments in the other country were not measured.

Wilcoxon rank sum tests were performed to: i) examine whether the exposures across the matched microenvironments in Australia and Belgium were different, ii) assess the exposure variability during the repeated measurements of a total of 20 microenvironments – Australia (n=13) and Belgium (n=7), iii) to evaluate if total, total DL, total UL and total broadcast median exposures across urban and rural/suburban microenvironments, as well as mobile and stationary microenvironments were different, and iv) to examine the difference between indoor and outdoor ISM 2.4 exposures. Furthermore, Spearman's rank correlation analysis was performed to examine the correlations between the median exposures of the compared microenvironments (n=17) in the two countries.

For all statistical tests, $p < 0.05$ (two sided) was considered as statistically significant. Data analysis was carried out with STATA ver13.1 (StataCorp, College Station, TX, USA).

3. Results

3.1. Calibration of the exposimeters

Table 1 shows the results of the on-body calibration of the ExpoM-RF 64 attached to the left lateral hip of the subject as indicated in Fig. 1. The response and 50% prediction interval for each band are denoted by R and PI_{50}, respectively. The calculated geometric mean responses are denoted by R_{gm}.

Table B1 (Appendix B) shows the measured cross-talk of ExpoM-RF 64 on the body of the calibrated subject. The cross-talk was determined using only the central frequencies of the bands. The cross-talk matrix was diagonal dominant and had a very small amount of off-body elements which were relatively high. The cross-talk of DECT induced in the 1800 DL band was relatively large (approximately half the value of the response) and the cross-talk of WiMAX 3.5 induced in the ISM 5.8 was relatively large as well, although less important since WiMAX was less common (see Table 1). The ISM 5.8 band generally suffered the most from cross-talk. Similarly, DVB-T induced most cross-talk in other frequency bands, since it was the lowest frequency band. Table B2 (Appendix B) lists the cross-talk matrix measured in the free space. The matrix was diagonal-dominant upper, central and lower frequencies.

3.2. Data characteristics

The measured exposure data of both exposimeters demonstrated varying degrees of censoring (Table A1, Appendix A), depending upon the type of frequency band and microenvironment. The amount of censoring also varied between ExpoM-RF 40 and ExpoM-RF 64 measured data at the same microenvironment. Of all frequency-specific microenviromental measurements, 47% of the data in Australia and 50% of the data in Belgium had 50% or more censored data, when measured with both ExpoM-RFs. The proportion of censoring across the measured frequency bands was much higher for the measurements performed at suburban and rural microenvironments compared to those at urban microenvironments. In general, the three frequency bands demonstrating the least proportion of censoring in both countries were: 900 MHz DL, 2100 MHz DL and ISM 2.4 GHz. The bands of 800 UL, 1800 UL, 1900 MHz UL, WiMAX 3.5 and ISM 5.8 in both countries, plus 2600 UL and 2600 DL in Australia, were amongst those demonstrating highest proportions of censoring.

Of all frequency band-specific microenvironmental measurements falling above the LODs, only 11% of the data in Australia and 18% of the data in Belgium followed lognormal distributions. Overall, the correlation of frequency-specific estimated median exposure levels measured with ExpoM-RF 40 and ExpoM-RF 64, from all microenvironments in both countries, showed high to very high positive correlations: Spearman rank correlation coefficients (r_s), 0.84–1 (Australia) and 0.72–0.99 (Belgium).

3.3. Descriptive statistics

Personal RF-EMF exposure across the measured frequency bands of all microenvironments in Australia and Belgium are summarized in Table 2 in terms of mean, median, 25th, 75th, and 95th percentiles. The five exposure sources providing the highest median exposures in Australia were: 1800 MHz DL, 900 MHz DL and 900 MHz UL (0.07 V/m); 2100 MHz DL (0.04 V/m); DECT and DVB-T (0.02 V/m). Similarly, 900 MHz DL (0.11 V/m), 2100 MHz DL (0.07 V/m), 1800 MHz DL (0.06 V/m), DVB-T and FM radio (0.05 V/m) provided the five highest median exposures in Belgium.

Table 2 also compares the exposure levels measured with a single non-on-body calibrated exposimeter (ExpoM-RF 64) vs those with two concurrently employed on-body calibrated exposimeters (ExpoM-RF 64 and ExpoM-RF 40). The exposures measured with the two exposimeters were nearly 2–3 times higher than those measured with the single exposimeter. However, this was not the case for FM, ISM 2.4 GHz, 2600 UL and DL, where the exposure levels were of similar values.

Table 3 summarizes the descriptive statistics (mean, median, 25th, 75th, and 95th percentiles) of the personal RF-EMF exposure levels for total, total downlink, total uplink and total broadcast across different microenvironments in Australia and Belgium.

In Australia, the five highest total median exposure levels measured were: city center (4.33 V/m), residential outdoor (urban) (0.75 V/m), park (0.75 V/m), bicycle (urban) (0.71 V/m), and train station (0.48 V/m). Likewise, the five lowest total median exposure levels measured were: mountain forest (rural) (0.02 V/m), shopping center (urban) (0.04 V/m), residential indoor (rural/suburban) (0.05 V/m), car (urban/suburban) (0.05 V/m), and office indoor (urban) (0.06 V/m).

In Belgium, the five highest total median exposures measured were: tram station (1.95 V/m), city center (0.95 V/m), park (0.90 V/m), residential outdoor (urban) (0.87 V/m), and library (0.77 V/m). Similarly, the five lowest total median exposure levels measured were: residential indoor (rural/suburban) (0.04 V/m), residential outdoor (rural/suburban) (0.07 V/m), office indoor (urban) (0.10 V/m), car (rural/suburban) (0.11 V/m), and bicycle (rural/suburban) (0.12 V/m).

3.4. Comparison of microenvironmental exposures

Of 17 microenvironmental total exposures measured in each country, only eight microenvironments in Belgium followed lognormal distributions, whereas six followed lognormal and two normal distributions in Australia. The other microenvironmental total exposure data followed neither lognormal nor normal distributions.

The Wilcoxon rank sum tests showed that total exposure for nine microenvironments in Australia were lower than the exposure across the corresponding microenvironments in Belgium ($p < 0.05$) (Table 4). However, the exposure in Australia was found to be higher than the corresponding exposure in Belgium for the five microenvironments ($p < 0.05$) – city center, tram, train, residential outdoor (rural/suburban), and residential indoor (rural/suburban) and the airport. Furthermore, the total exposure levels for the bicycle (urban) and bus microenvironments in Australia and Belgium did not show any significant difference. Although the train station microenvironment in Australia provided higher exposure than that in Belgium, the difference was not statistically significant ($p = 0.32$).

The microenvironmental comparisons for total and total DL median exposures in both countries showed strong positive correlations: $r_s = 0.74$ ($p = 0.006$) for total, and $r_s = 0.73$ ($p = 0.0007$) for total DL exposures. Furthermore, there were no significant or weak correlations for the total UL and total broadcast exposures ($r_s = 0.086$, $p = 0.74$ for total UL, and $r_s = 0.46$, $p = 0.06$ for total broadcast).

In Australia, total, total DL, and total UL exposures across urban microenvironments were higher than those across rural/suburban microenvironments ($p = 0.03$). However, there was no difference between urban and rural/suburban microenviromental exposures for total broadcast ($p = 0.28$). Nor were there significant differences in total, total DL, total UL and total broadcast exposures between mobile and stationary microenvironments ($p = 0.64$–0.90).

In Belgium, total, total DL and total broadcast exposures in urban microenvironments were higher than those in rural/suburban microenvironments ($p = 0.006$ for total, $p = 0.02$ for total DL, and 0.01 for total broadcast). Whereas there was no difference in the total UL exposure in urban and that in rural/suburban microenvironments ($p = 0.09$). There were no significant

Table 2
Summary of the frequency-specific and total personal RF-EMF exposure levels of all microenvironments in Australia (n=19) and Belgium (n=19) [single non-on-body calibrated ExpoM-RF 64 data vs concurrently used on-body calibrated ExpoM-RF 64 and ExpoM-RF 40 data].

Frequency bands	Summary statistics (mean, median, 25th, 75th and 95th percentiles)							
	Australia				Belgium			
	E_{rms} (with a single exposimeter)		E_{rms} (with two exposimeters)		E_{rms} (with a single exposimeter)		E_{rms} (with two exposimeters)	
	Mean (SD)	median (25th, 75th and 95th percentiles)	Mean (SD)	median (25th, 75th and 95th percentiles)	Mean (SD)	median (25th, 75th and 95th percentiles)	Mean (SD)	median (25th, 75th and 95th percentiles)
FM radio (87.5–108 MHz)	0.02 (0.03)	0.01 (0.01, 0.03, 0.14)	0.03 (0.03)	0.01 (0.01, 0.03, 0.13)	0.05 (0.03)	0.04 (0.01, 0.08, 0.10)	0.05 (0.04)	0.05 (0.01, 0.09, 0.12)
DVB-T (470–790 MHz)	0.03 (0.06)	0.007 (0.003, 0.04, 0.25)	0.08 (0.15)	0.02 (0.007, 0.08, 0.69)	0.03 (0.03)	0.02 (0.003, 0.05, 0.09)	0.07 (0.07)	0.05 (0.007, 0.11, 0.23)
800 UL (832–862 MHz)	0.009 (0.01)	0.003 (0.005, 0.01, 0.05)	0.02 (0.02)	0.009 (0.006, 0.02, 0.10)	0.003 (0.005)	0.003 (0.003, 0.003, 0.005)	0.007 (0.001)	0.006 (0.006, 0.006, 0.01)
800 DL (791–821 MHz)	0.005 (0.002)	0.003 (0.003, 0.006, 0.01)	0.009 (0.004)	0.007 (0.007, 0.01, 0.02)	0.05 (0.07)	0.02 (0.008, 0.09, 0.23)	0.10 (0.14)	0.03 (0.01, 0.19, 0.47)
900UL (880–915 MHz)	0.04 (0.03)	0.03 (0.008, 0.06, 0.12)	0.08 (0.07)	0.07 (0.01, 0.11, 0.26)	0.008 (0.009)	0.003 (0.003, 0.005, 0.03)	0.01 (0.01)	0.007 (0.007, 0.01, 0.05)
900 DL (925–960 MHz)	0.08 (0.12)	0.03 (0.01, 0.12, 0.56)	0.24 (0.40)	0.07 (0.03, 0.31, 1.78)	0.13 (0.17)	0.07 (0.03, 0.24, 0.71)	0.30 (0.35)	0.11 (0.06, 0.54, 1.37)
1800 UL (1710–1785 MHz)	0.005 (0.005)	0.003 (0.003, 0.003, 0.02)	0.01 (0.01)	0.007 (0.007, 0.01, 0.06)	0.005 (0.002)	0.003 (0.003, 0.005, 0.01)	0.01 (0.007)	0.007 (0.007, 0.009, 0.03)
1800 DL (1805–1880 MHz)	0.10 (0.21)	0.03 (0.01, 0.11, 0.93)	0.27 (0.58)	0.08 (0.03, 0.28, 2.62)	0.06 (0.08)	0.02 (0.005, 0.09, 0.37)	0.14 (0.21)	0.06 (0.01, 0.23, 0.87)
DECT (1880–1900 MHz)	0.03 (0.05)	0.008 (0.003, 0.03, 0.24)	0.07 (0.14)	0.02 (0.007, 0.06, 0.61)	0.02 (0.04)	0.01 (0.003, 0.02, 0.18)	0.05 (0.08)	0.03 (0.007, 0.05, 0.37)
1900 UL (1920–1980 MHz)	0.007 (0.01)	0.002 (0.002, 0.003, 0.06)	0.01 (0.02)	0.003 (0.003, 0.006, 0.10)	0.003 (0.003)	0.002 (0.002, 0.003, 0.01)	0.005 (0.005)	0.003 (0.003, 0.007, 0.02)
2100 DL (2110–2170 MHz)	0.09 (0.25)	0.02 (0.004, 0.08, 1.13)	0.17 (0.49)	0.04 (0.007, 0.12, 2.18)	0.07 (0.09)	0.03 (0.008, 0.11, 0.39)	0.12 (0.16)	0.07 (0.01, 0.20, 0.68)
ISM 2.4 (2400–2485 MHz)	0.02 (0.02)	0.01 (0.01, 0.02, 0.06)	0.01 (0.01)	0.01 (0.008, 0.01, 0.06)	0.02 (0.01)	0.02 (0.01, 0.02, 0.05)	0.02 (0.01)	0.02 (0.008, 0.02, 0.04)
2600 UL (2500–2570 MHz)	0.002 (0.001)	0.002 (0.002, 0.002, 0.006)	0.002 (0.001)	0.002 (0.002, 0.002, 0.005)	0 (0)	0 (0, 0, 0)	0 (0)	0 (0, 0, 0)
2600 DL (2620–2690 MHz)	0.03 (0.07)	0.002 (0.002, 0.02, 0.33)	0.04 (0.11)	0.003 (0.003, 0.03, 0.47)	0 (0)	0 (0, 0, 0)	0 (0)	0 (0, 0, 0)
WiMAX 3.5 (3400–3600 MHz)	0.002 (0.002)	0.002 (0.002, 0.02, 0.009)	0.003 (0.003)	0.003 (0.003, 0.003, 0.01)	0.003 (0.006)	0.002 (0.002, 0.002, 0.02)	0.003 (0.004)	0.003 (0, 0.003, 0.02)
ISM 5.8 (5150–5875 MHz)	0.02 (0.06)	0 (0, 0.03, 0.26)	0.01 (0.02)	0 (0, 0.01, 0.11)	0.02 (0.02)	0 (0, 0.03, 0.08)	0.0006 (0.008)	0 (0, 0.01, 0.003)
Total	0.20 (0.36)	0.10 (0.03, 0.19, 1.67)	0.52 (0.95)	0.38 (0.06, 0.48, 4.34)	0.21 (0.22)	0.12 (0.07, 0.33, 0.95)	0.46 (0.47)	0.30 (0.12, 0.77, 1.95)

Abbreviations: DVB-T: Digital Video Broadcasting–Terrestrial, DL: Downlink, DECT: Digital Enhanced Cordless Telecommunications, FM: Frequency Modulated, ISM: Industrial, Scientific and Medical, SD: Standard deviation, UL: Uplink, WiMAX: Worldwide Interoperability for Microwave Access; †majority of the measured data have replaced values of the LOD/$\sqrt{2}$ for these frequency bands

Table 3
Personal total, total downlink, total uplink and total broadcast exposures (E_{rms}) across various microenvironments in Australia (n=19) and Belgium (n=19).

Microenvironments	Total (V/m)			Total downlink (V/m)			Total uplinks (V/m)			Total broadcast (V/m)		
	Mean (SD)	Median	25th, 75th & 95th percentiles	Mean (SD)	Median	25th, 75th & 95th percentiles	Mean (SD)	Median	25th, 75th & 95th percentiles	Mean (SD)	Median	25th, 75th & 95th percentiles
Residential outdoor (urban)												
Australia	0.93 (0.62)	0.75	0.41, 1.32, 2.05	0.90 (0.61)	0.70	0.39, 1.28, 2.01	0.17 (0.10)	0.14	0.10, 0.22, 0.36	0.05 (0.02)	0.04	0.03, 0.05, 0.08
Belgium	0.92 (0.40)	0.87	0.70, 1.13, 1.64	0.91 (0.40)	0.86	0.68, 1.12, 1.64	0.01 (0.004)	0.01	0.01, 0.01, 0.02	0.11 (0.04)	0.11	0.09, 0.14, 0.18
Residential indoor (urban)												
Australia	0.15 (0.06)	0.13	0.10, 0.20, 0.26	0.14 (0.06)	0.11	0.09, 0.19, 0.24	0.05 (0.01)	0.04	0.04, 0.06, 0.08	0.02 (0.004)	0.02	0.02, 0.02, 0.03
Belgium	0.24 (0.08)	0.25	0.20, 0.30, 0.37	0.23 (0.08)	0.23	0.18, 0.28, 0.35	0.05 (0.01)	0.01	0.01, 0.03, 0.04	0.07 (0.03)	0.07	0.05, 0.08, 0.12
Office indoor (urban)												
Australia	0.07 (0.02)	0.06	0.05, 0.09, 0.10	0.05 (0.02)	0.04	0.03, 0.06, 0.07	0.02 (0.01)	0.02	0.02, 0.03, 0.05	0.03 (0.01)	0.02	0.01, 0.04, 0.05
Belgium	0.11 (0.06)	0.10	0.074, 0.14, 0.23	0.07 (0.03)	0.061	0.05, 0.08, 0.15	0.03 (0.02)	0.02	0.01, 0.03, 0.08	0.02 (0.004)	0.01	0.01, 0.02, 0.02
Park (urban)												
Australia	0.75 (0.45)	0.75	0.38, 0.95, 1.30	0.70 (0.44)	0.70	0.34, 0.90, 1.26	0.19 (0.10)	0.17	0.11, 0.25, 0.41	0.08 (0.03)	0.08	0.06, 0.10, 0.14
Belgium	0.96 (0.45)	0.90	0.59, 1.18, 1.82	0.90 (0.46)	0.85	0.54, 1.13, 1.77	0.01 (0.004)	0.01	0.01, 0.01, 0.02	0.25 (0.09)	0.26	0.20, 0.31, 0.39
City center												
Australia	4.50 (1.31)	4.33	3.55, 5.34, 6.84	4.36 (1.31)	4.20	3.42, 5.18, 6.62	0.31 (0.11)	0.29	0.24, 0.35, 0.55	0.73 (0.23)	0.69	0.56, 0.86, 1.21
Belgium	1.16 (0.70)	0.95	0.58, 1.65, 2.42	1.12 (0.70)	0.93	0.54, 1.61, 2.37	0.03 (0.02)	0.02	0.02, 0.03, 0.06	0.20 (0.06)	0.02	0.16, 0.23, 0.30
Library (urban)												
Australia	0.11 (0.03)	0.10	0.09, 0.12, 0.15	0.09 (0.02)	0.09	0.07, 0.10, 0.13	0.04 (0.01)	0.04	0.04, 0.05, 0.06	0.02 (0.002)	0.02	0.01, 0.02, 0.02
[a]Belgium	0.99 (0.51)	0.77	0.63, 1.22, 2.02	0.94 (0.47)	0.74	0.60, 1.18, 1.92	0.01 (0.001)	0.01	0.01, 0.01, 0.01	0.14 (0.04)	0.14	0.11, 0.16, 0.20
Shopping center (urban)												
Australia	0.06 (0.05)	0.04	0.04, 0.05, 0.14	0.04 (0.04)	0.02	0.02, 0.03, 0.09	0.03 (0.02)	0.02	0.01, 0.03, 0.06	0.02 (0.02)	0.02	0.01, 0.02, 0.06
[a]Belgium	0.14 (0.05)	0.13	0.10, 0.17, 0.24	0.08 (0.05)	0.07	0.05, 0.09, 0.16	0.07 (0.05)	0.06	0.04, 0.08, 0.14	0.06 (0.04)	0.04	0.03, 0.07, 0.13
Train station (urban)												
Australia	0.47 (0.13)	0.48	0.39, 0.55, 0.64	0.40 (0.11)	0.41	0.32, 0.47, 0.56	0.08 (0.04)	0.07	0.06, 0.09, 0.16	0.10 (0.08)	0.08	0.07, 0.11, 0.18
[a]Belgium	0.89 (1.14)	0.30	0.13, 1.14, 3.29	0.82 (1.12)	0.11	0.07, 1.12, 3.15	0.06 (0.04)	0.05	0.03, 0.08, 0.14	0.11 (0.06)	0.12	0.08, 0.14, 0.18
Train												
Australia	0.42 (0.23)	0.38	0.25, 0.54, 0.8	0.17 (0.14)	0.13	0.06, 0.23, 0.49	0.32 (0.26)	0.02	0.11, 0.45, 0.77	0.06 (0.06)	0.05	0.02, 0.08, 0.19
Belgium	0.34 (0.32)	0.24	0.14, 0.40, 1.02	0.13 (0.10)	0.11	0.05, 0.17, 0.32	0.25 (0.35)	0.09	0.03, 0.32, 1.02	0.05 (0.07)	0.01	0.01, 0.04, 0.20
Tram station (urban)												
Australia	0.44 (0.11)	0.43	0.36, 0.51, 0.64	0.40 (0.10)	0.40	0.32, 0.47, 0.60	0.11 (0.03)	0.11	0.09, 0.13, 0.17	0.11 (0.03)	0.11	0.09, 0.13, 0.16
[a]Belgium	1.97 (0.48)	1.95	1.61, 2.32, 2.77	1.91 (0.46)	1.91	1.58, 2.23, 2.69	0.02 (0.01)	0.01	0.01, 0.02, 0.03	0.18 (0.04)	0.17	0.15, 0.20, 0.24
Tram (urban)												
Australia	0.62 (0.44)	0.47	0.33, 0.78, 1.52	0.53 (0.46)	0.39	0.19, 0.69, 1.47	0.17 (0.11)	0.15	0.09, 0.23, 0.38	0.15 (0.08)	0.12	0.09, 0.19, 0.30
[a]Belgium	0.53 (0.35)	0.43	0.24, 0.75, 1.20	0.45 (0.38)	0.33	0.14, 0.71, 1.18	0.04 (0.04)	0.02	0.01, 0.05, 0.16	0.17 (0.11)	0.15	0.11, 0.20, 0.37
Bus (urban)												
Australia	0.45 (0.29)	0.45	0.17, 0.65, 0.93	0.39 (0.27)	0.40	0.12, 0.58, 0.82	0.15 (0.12)	0.12	0.08, 0.19, 0.40	0.09 (0.06)	0.08	0.04, 0.13 0.20
[a]Belgium	0.45 (0.28)	0.41	0.22, 0.61, 1.01	0.33 (0.25)	0.26	0.16, 0.45, 0.76	0.03 (0.03)	0.02	0.01, 0.04, 0.10	0.25 (0.21)	0.19	0.09, 0.36, 0.70
Subway station & ride (urban)												
[a]Australia	0.43 (0.19)	0.41	0.32, 0.54, 0.75	0.19 (0.11)	0.20	0.09, 0.27, 0.40	0.21 (0.22)	0.10	0.05, 0.32, 0.68	0.12 (0.08)	0.12	0.04, 0.18, 0.24
Airport indoor												
[a]Australia	0.27 (0.13)	0.24	0.17, 0.35, 0.51	0.15 (0.16)	0.05	0.04, 0.26, 0.47	0.16 (0.10)	0.12	0.08, 0.21, 0.38	0.16 (0.10)	0.01	0.01, 0.02, 0.11
[a]Belgium	0.17 (0.05)	0.16	0.13, 0.20, 0.26	0.15 (0.05)	0.14	0.11, 0.17, 0.24	0.06 (0.04)	0.05	0.04, 0.08, 0.13	0.02 (0.003)	0.01	0.01, 0.01, 0.02

Table 3 (*continued*)

Microenvironments	Total (V/m)			Total downlink (V/m)			Total uplinks (V/m)			Total broadcast (V/m)		
	Mean (SD)	Median	25th, 75th & 95th percentiles	Mean (SD)	Median	25th, 75th & 95th percentiles	Mean (SD)	Median	25th, 75th & 95th percentiles	Mean (SD)	Median	25th, 75th & 95th percentiles
Bicycle (urban)												
Australia	0.90 (0.65)	0.71	0.40, 1.22, 2.34	0.82 (0.63)	0.64	0.33, 1.14, 2.19	0.21 (0.17)	0.14	0.09, 0.28, 0.55	0.21 (0.16)	0.01	0.01, 0.02, 0.05
[a]Belgium	0.78 (0.30)	0.73	0.57, 0.97, 1.33	0.74 (0.31)	0.69	0.55, 0.93, 1.29	0.01 (0.02)	0.01	0.01, 0.01, 0.02	0.02 (0.07)	0.20	0.15, 0.25, 0.31
Bicycle (rural/suburban)												
[a]Belgium	0.15 (0.09)	0.12	0.09, 0.18, 0.36	0.15 (0.09)	0.11	0.08, 0.17, 0.36	0.01 (0.002)	0.01	0.01, 0.01, 0.01	0.02 (0.002)	0.01	0.01, 0.01, 0.02
Car (urban/suburban) Australia	0.07 (0.06)	0.05	0.03, 0.09, 0.22	0.06 (0.06)	0.03	0.02, 0.06, 0.19	0.02 (0.02)	0.01	0.01, 0.02, 0.07	0.02 (0.02)	0.01	0.01, 0.02, 0.06
Belgium	0.40 (0.26)	0.31	0.20, 0.54, 0.95	0.37 (0.26)	0.29	0.18, 0.52, 0.92	0.01 (0.01)	0.01	0.01, 0.01, 0.03	0.09 (0.06)	0.08	0.06, 0.11, 0.22
Car (rural/suburban)												
[a]Belgium	0.14 (0.11)	0.11	0.05, 0.19, 0.35	0.12 (0.11)	0.09	0.03, 0.18, 0.33	0.01 (0.007)	0.01	0.01, 0.01, 0.01	0.02 (0.01)	0.01	0.01, 0.01, 0.05
Residential outdoor (rural/suburban)												
Australia	0.09 (0.02)	0.10	0.08, 0.11, 0.12	0.08 (0.02)	0.08	0.07, 0.09, 0.10	0.03 (0.008)	0.03	0.02, 0.03, 0.04	0.04 (0.01)	0.03	0.03, 0.04, 0.06
Belgium	0.07 (0.04)	0.07	0.05, 0.09, 0.12	0.07 (0.03)	0.06	0.04, 0.09, 0.12	0.01 (0.03)	0.01	0.01, 0.01, 0.01	0.01 (0.001)	0.01	0.01, 0.01, 0.02
Residential indoor (rural/suburban)												
[a]Australia	0.05 (0.01)	0.05	0.04, 0.05, 0.06	0.03 (0.002)	0.03	0.03, 0.03, 0.03	0.01 (0.006)	0.01	0.01, 0.01, 0.01	0.03 (0.01)	0.03	0.02, 0.04, 0.05
Belgium	0.04 (0.03)	0.04	0.03 0.04, 0.09	0.02 (0.001)	0.02	0.02, 0.02, 0.02	(0.005)	0.01	0.01, 0.01, 0.01	0.01 (0.0002)	0.01	0.01, 0.01, 0.01
Mountain/forest (rural)												
[a]Australia	0.02 (0.0007)	0.02	0.02, 0.02, 0.02	0.01 (0.0005)	0.01	0.01, 0.02, 0.02	0.007 (0)	0.007	0.007, 0.007, 0.007	0.007 (0)	0.01	0.01, 0.01, 0.01

[a]Single measurement, SD: Standard deviation.

Table 4
Evaluation of the variability in total personal exposure (V/m) during the 1st (m_1) and 2nd measurements (m_2) in Australia (n=13) and Belgium (n=7).

Microenvironments	Total exposure levels (m_1) [V/m]			Total exposure levels (m_2) [V/m]			†p values
	Mean (SD)	Median	25th, 75th & 95th percentiles	Mean (SD)	Median	25th, 75th & 95th percentiles	
Residential outdoor (urban)							
Australia	1.06 (0.68)	0.89	0.46, 1.57, 2.40	0.80 (0.52)	0.67	0.38, 1.10, 1.68	< **0.001**
Belgium	0.93 (0.37)	0.90	0.73, 1.14, 1.56	0.91 (0.42)	0.85	0.67, 1.13, 1.72	0.16
Residential indoor (urban)							
Australia	0.18 (0.05)	0.19	0.13, 0.22, 0.27	0.12 (0.04)	0.11	0.10, 0.12, 0.23	< **0.001**
Belgium	0.20 (0.07)	0.21	0.13, 0.25, 0.30	0.29 (0.08)	0.30	0.25, 0.33, 0.41	< **0.001**
Office indoor (urban)							
Australia	0.06 (0.02)	0.06	0.05, 0.07, 0.10	0.07 (0.02)	0.08	0.04, 0.09, 0.10	0.19
Belgium	0.13 (0.07)	0.11	0.08, 0.16, 0.31	0.09 (0.04)	0.08	0.06, 0.12, 0.16	< **0.001**
Park (urban)							
Australia	0.69 (0.32)	0.67	0.45, 0.89, 1.16	0.79 (0.52)	0.79	0.35, 0.99, 1.43	0.05
Belgium	0.87 (0.36)	0.80	0.56, 1.13, 1.54	1.07 (0.52)	0.98	0.73, 1.25, 2.12	< **0.001**
City center							
Australia	4.58 (1.30)	4.39	3.61, 5.24, 7.13	4.38 (1.32)	4.28	3.27, 5.51, 6.41	0.17
Library (urban)							
Australia	0.10 (0.02)	0.10	0.09, 0.11, 0.14	0.11 (0.03)	0.11	0.08, 0.13, 0.16	0.06
Train station (urban)							
Australia	0.50 (0.09)	0.51	0.43, 0.57, 0.62	0.44 (0.15)	0.43	0.32, 0.52, 0.65	< **0.001**
Train							
Australia	0.48 (0.17)	0.46	0.37, 0.59, 0.78	0.37 (0.27)	0.28	0.20, 0.45, 0.84	< **0.001**
Belgium	0.17 (0.09)	0.14	0.10, 0.29, 0.36	0.50 (0.38)	0.38	0.23, 0.60, 1.33	< **0.001**
Tram station (urban)							
Australia	0.50 (0.10)	0.49	0.43, 0.55, 0.67	0.38 (0.08)	0.37	0.32, 0.43, 0.53	< **0.001**
Tram (urban)							
Australia	0.59 (0.45)	0.46	0.23, 0.73, 1.52	0.65 (0.42)	0.49	0.38, 0.80, 1.56	< **0.001**
Bicycle (urban)							
Australia	0.88 (0.66)	0.74	0.33, 1.23, 2.28	0.93 (0.65)	0.69	0.44, 1.22, 2.42	**0.04**
Bus (urban)							
Australia	0.43 (0.33)	0.38	0.13, 0.67, 0.97	0.47 (0.24)	0.50	0.25, 0.63, 0.89	**0.004**
Car (urban)		0.28	0.17, 0.47, 0.83		0.34	0.22, 0.58, 1.08	< **0.001**
Residential indoor (rural/suburban)							
Belgium	0.04 (0.01)	0.03	0.03, 0.04, 0.08	0.05 (0.03)	0.04	0.03, 0.04, 0.10	< **0.001**
Residential outdoor (rural/suburban)							
Australia	0.09 (0.02)	0.09	0.08, 0.10, 0.12	0.10 (0.02)	107	0.09, 0.11, 0.13	< **0.001**
Belgium	0.08 (0.05)	0.07	0.05, 0.10, 0.13	0.07 (0.02)	0.06	0.05, 0.08, 0.11	**0.002**

†p values < 0.05 statistically significant different exposure levels, SD: Standard deviation

differences in total, total DL, total UL and total broadcast exposures between mobile and stationary microenvironments ($p=0.36$–0.96).

3.5. Assessment of the variability in exposures

Wilcoxon rank sum tests were undertaken to evaluate the repeated measurements of the RF-EMF exposure levels. The results have been tabulated in Table 4. Overall, half of the microenvironments (10 of 20 in both countries) showed that repeated measurements provided different total median exposure levels.

Of the 13 microenvironments repeated in Australia, nine showed statistically different total exposure levels at the first and second measurements ($p < 0.001$–0.04) (Table 4), whereas four did not show any significant difference ($p > 0.05$) between the exposure levels. For the tram and residential outdoor (rural/suburban) microenvironments, the total exposures during the two measurement sessions showed little difference, though the p values were statistically significant.

Of the seven microenvironments repeated in Belgium, six showed statistically different total exposure levels at the first and second measurements ($p < 0.001$–0.002). However, despite having significant p values, office indoor (urban), residential indoor, and residential outdoor (rural/suburban) provided a little difference in exposure between the first and second measurements. Residential outdoor (urban) did not show statistically significant variation in the exposure levels measured during the repeated measurements ($p=0.16$).

4. Discussion

We have evaluated far-field personal RF-EMF exposures across the different microenvironments in Australia and Belgium by employing two on-body calibrated exposimeters. Measurement of exposures in microenvironments allowed us to: i) identify typical exposure levels in the specific microenvironments, ii) monitor exposure trends across these microenvironments over time, and iii) help characterize personal exposure assuming a person occupies a specific microenvironment for a certain amount of time (Dürrenberger et al., 2014). Since most of our exposure data characterized non-normal or non-lognormal distribution, we have preferred to present our results in terms of median and percentiles. Similar presentation of RF-EMF summary statistics have been provided elsewhere (e.g. Bhatt et al., 2016a; Najera et al., 2016). The use of two exposimeters to assess exposure in this study demonstrated that the exposimeters may measure different amounts of RF-EMF signals simultaneously whilst on the body. The proportion of detected signals was high for the mobile phone DL and Wi-Fi bands, which is due to the fact that these signals were relatively common across all microenvironments.

4.1. Exposure characteristics in Australia and Belgium

Our study found that mobile phone base downlink exposures contributed the largest share to total exposures (Table 3). Similar results have been reported elsewhere (e.g. Sagar et al., 2016; Urbinello et al., 2014c). The usage of mobile phones and degree of evolution of mobile phone network signals (e.g. Global System for Mobile communication 900 and 1800, Universal Mobile Telecommunications System, and Long-Term Evolution) in Australia and Belgium are not quite the same (International Telecommunication Union, 2010; Kumar, 2004; SpectrumMonitoring, 2016a, 2016b). This perhaps explains the different contribution of frequency band-specific exposures to total RF-EMF exposure in the two countries. We also demonstrated that the concurrent use of two on-body calibrated exposimeters provided the average exposure levels of 1.35 and 1.6 times higher in Australia and Belgium respectively, than those provided with a single non-on-body calibrated exposimeter. This is in line with earlier studies (Bolte et al., 2011; Neubauer et al., 2010; Thielens et al., 2015a) that demonstrated that a non-on-body calibrated exposimeter would underestimate personal exposure to incident RF EMFs due to the shielding of the body. Previous controlled measurements or modelling studies (Blas et al., 2007; Iskra et al., 2010; Neubauer et al., 2010) also found an underestimation of RF-EMF exposures due to body shielding, which is comparable to that estimated in our study. Future research should investigate this further in order to better explain the magnitude of effect that body shielding may have in underestimating microenvironmental personal RF-EMF exposure measurements.

Mobile phone frequency bands of 2600 MHz, WiMax 3.5 GHz, and ISM 5.8 GHz provided very little exposure. In Melbourne, 2600 MHz has recently been allocated to be used by mobile network providers; however, signals are mostly limited to some urban areas. The band has been officially sold for use in Belgium, but operation has not yet started (SpectrumMonitoring, 2016b). ISM 2.4 GHz shared a small portion of total exposures in both countries (see Table 2), and overall, there was no significant difference between indoor and outdoor microenviromental Wi-Fi 2.4 exposures in either country (results not shown).

Three or four microenvironments in the two countries shared the highest total exposures: the city center, urban parks, and outdoor residential areas. The fourth was a tram station in Belgium, which was located in the city center. The total exposure differences observed across the microenvironments in these two countries may be attributed to the differences in population density and physical infrastructure of Ghent and Melbourne. The exposure difference between the compared microenvironments in both countries was likely to be largely due to the contribution of total downlink exposure, which is generally higher for the microenvironments in Belgium.

The city center, train and airport in Australia (Melbourne) demonstrated higher exposures compared to the corresponding microenvironments in Belgium. Melbourne city center has higher population density and larger number of base stations providing higher capacity of telecommunication signals compared to the Ghent city center (OpenSignal, 2016; Antenna Site Register, 2016). The train travels in both countries involved journeys through the respective open areas of Melbourne and Ghent. In case of the train travel in Melbourne, high mobile phone signals can occur within the urban region (OpenSignal, 2016), especially with many people on board. Contrary to this, train travel from Ghent to Antwerp, a journey mostly through suburban and rural regions, the strength of RF-EMF signals, particularly of mobile phone base stations was weaker (Antenna Site Register, 2016). The total downlink exposure in the train in Belgium was found to be lower than that in the train in Australia, whereas the total uplink exposure scenario was found to be the opposite. This may be due to a higher path loss between the user and the network, which increases the DL signal that can reach the user and simultaneously increases the UL signal that is necessary to connect to the network. Furthermore, the train in Belgium had windows with metallic coating (Bhatt et al., 2016a), which provided highly attenuated DL signals and the mobile phone has to transmit at a higher power level to get past the metallic coating. Car travel in Australia was done in a less dense urban and suburban area of Melbourne, unlike in Belgium where it was mostly in highly dense urban areas. The resultant lower exposures in Australia for urban car travel were most likely due to this lower urban density.

The total exposure levels, including total DL and total uplink exposures, measured in our study are higher than those reported for similar European microenvironments, including Ghent (Bolte and Eikelboom, 2012; Joseph et al., 2010; Urbinello et al., 2014a, 2014b, 2014c). This could be because these studies did not correct for the consequence of body shielding on the measured personal exposure levels, which generally underestimates personal exposure levels (Bolte et al., 2011; Neubauer et al., 2010; Thielens et al., 2015a). However our study took this issue into account by using frequency-specific on-body calibration factors while estimating personal exposure levels. Furthermore, previous studies used different protocols (e.g. a single non-on-body calibrated exposimeter), measurement devices and analysis approaches compared to ours. Our study observed that personal exposures in urban microenvironments were much higher than those in rural and suburban microenvironments in Australia and Belgium. Furthermore, the exposure levels across indoor microenvironments were much lower than those across outdoor microenvironments. These findings are in line with the studies conducted in Europe (Bolte and Eikelboom, 2012; Joseph et al., 2010; Urbinello et al., 2014a, Vermeeren et al., 2013). In general, mobile phone base station exposure, the principal contributor to total RF-EMF exposure, is generally stronger in urban environments compared to rural and suburban environments (Antenna Site Register, 2016; OpenSignal, 2016; Radio Frequency National Site Archive, 2016). Amongst indoor stationary microenvironments, the library in Belgium and the airport in Australia provided the highest exposure levels. Interestingly, the library in Ghent was about 200 m from a nearby base station, which was exactly in line-of-sight. This also applied to the tram station in Ghent, which characterized the highest exposure level for outdoor microenvironments in Belgium.

The results demonstrated that total RF-EMF exposure levels varied for the majority of microenvironments in both countries. It is likely that relatively low dispersion of measurements (e.g. residential indoor and residential outdoor (rural/suburban) in Belgium) provide statistically significant differences in exposures, without having much differences in median exposures. While comparing these results, we therefore agree that exposure differences should not be solely interpreted on the basis of p-values (The American Statistical Association, 2016). Urbinello et al. (2014c) also showed that the environmental exposure levels of mobile phone DL signals varied across the same areas. Mobile phone DL signals, are the main contributor to the total exposure, and their subsequent variation, has a large effect in the total exposure. In general, diurnal variation in mobile phone signals in human environments is likely due to the variation of spatio-temporal factors (Manassas et al., 2012; Vermeeren et al., 2013; Urbinello et al., 2014c). Spatial factors, such as the location of the measurement sites (urban, suburban, rural, outdoor, indoor etc.), the proximity and number of nearby base stations; temporal factors (e.g. day, time and season when the measurements were performed), measurement path followed, and existing mobile phone traffic also affect the exposure levels (Bolte, 2016; Bolte and Eikelboom, 2012; Joseph and Verloock, 2010; Manassas et al., 2012; Roderíguez et al., 2011; Urbinello et al., 2014b; Viel et al., 2009; Vermeeren et al., 2013). The exposure variability in various microenvironments needs to be further examined with longer measurement times, at more spots within each microenvironment, and taking a greater number of repeated measurements controlling for spatio-temporal factors.

All exposure levels measured in our study were well below the reference levels for the general public as provided by the guidelines of the International Commission on Non-Ionizing Radiation Protection (ICNIRP, 1998) and the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) (Radiation Protection Standard, 2002). However, these guidelines are fundamentally designed to protect against acute (very short-term) RF-EMF health effects, particularly tissue heating. Biological effects have been shown at or below some levels we measured, including decrease in reproductive capacity, apoptotic cell death, and stress responses (Panagopoulos et al., 2010; Augner et al., 2010).

Since most of the exposure data measured in our study did not follow lognormal distributions, we were not able to apply a similar approach to deal with the censored data as used in previous studies (Bolte and Eikelboom, 2012; Frei et al., 2009; Joseph et al., 2010; Juhász et al., 2011; Urbinello et al., 2014a, 2014b). These studies used robust regression on order statistics (ROS) to treat the censored data in order to calculate summary statistics. In addition to ROS, there are other approaches to deal with censored data (i.e. non-detected): substitution, maximum likelihood estimation (MLE) methods, and Kaplan–Meier methods (Ganser and Hewett, 2010). However, the three most commonly used methods are substitution by LOD, LOD/2 and LOD/$\sqrt{2}$ (Hewett, 2007, Hewett and Ganser, 2007). The performance of these methods has been evaluated using simulations on single and contaminated lognormal data and it was found that LOD/$\sqrt{2}$ substitution method provided slightly positively biased means and negatively biased 95th percentiles, yet plausible results compared to more advanced approaches (Hewett and Ganser, 2007). Substitution methods have been used in RF-EMF personal exposure assessment elsewhere (Ibrani et al., 2016; Thomas et al., 2008; Röösli et al., 2008).

The evaluation of ROS and substitution (i.e. LOD) methods for RF-EMF exposure generally provided higher values of frequency band-specific summary statistics of exposures (i.e. means, medians, 25th, 75th and 95th percentiles) compared to the former method (Röösli et al., 2008). Röösli et al. (2008) also observed that the larger the proportion of censored data, the larger was the difference between the substitution (by LOD) and the ROS mean. The frequency-specific LODs for the exposimeter used in our study were lower compared to those employed in previous studies (EME SPY) (Bhatt et al., 2016b), which suggest that our devices were more sensitive than EME SPY.

4.2. Calibration of the exposimeters

As shown in Table 1, a majority (12 of 15) of the responses *R* were lower than 1, which indicated that the ExpoM-RF underestimated personal exposure in these frequency bands without compensation. The responses in the 2600 MHz and the ISM 2.4 band were close to one. In the ISM 5.8 band, we found an overestimation of exposure by uncorrected measurements. The same underestimation was demonstrated previously (Bolte et al., 2011), where all but one frequency band showed a response <1; and Thielens et al. (2015a) showed that all but two frequency bands showed a median response <1.

The PI_{50} values measured for the ExpoM-RF 64 ranged from 6.3 to 10 dB and no clear frequency dependence was observed. Thielens et al. (2015a) showed that the PI_{50} values measured for individual exposimeters worn on the hip ranged from approximately 7 to 13 dB. Bolte et al. (2011) demonstrated these values to be up to approximately 20 dB. The PI_{50} values are reduced in all frequency bands when an average over two ExpoM-RFs is considered, which is in agreement with previous findings (Thielens et al., 2015a; Bolte et al., 2011). The main reason for this reduction in PI_{50} is the mirrored RF-EMF pattern of both ExpoM-RFs with regard to the sagittal plane of the subject. For certain azimuthal angles of incidence of RF-EMFs, one ExpoM-RF experiences a reduction in received power due to shadowing of the body, while the other ExpoM-RF experiences less or no shadowing at the same time. This consequently results in a more isotropic, average RF-EMF pattern and provides less variation in the distribution of the geometric averaged response.

The high cross-talk shown by the ISM 5.8 band was expected since this frequency band was the highest one, and had the highest potential to register harmonics from lower frequency bands. Similarly, DVB-T induced most cross-talk in other frequency bands, since it was the lowest frequency band. The cross-talk measured DVB-T was closer to a diagonal matrix than the one reported by Thielens et al. (2015a) using another type of exposimeter (EME SPY), where more off-diagonal elements were observed. Though the cross-talk observed in this study was determined using only the central frequencies of the bands, in reality the signals can also be emitted at the edges of the frequency bands and could thus induce a higher cross talk. Therefore, we also calibrated the ExpoM-RF 64 in a free space, using not only the central frequency, but also the two edges of the frequency bands.

The differences in the diagonal elements (shown in Tables B1 and B2, Appendix B) were higher than those obtained on the body for the lowest 10 frequency bands and higher than those presented in Table B1 for the five highest frequency bands. This was expected since there was no attenuating body next to the ExpoM-RF in free space. The off-diagonal elements were relatively low in a majority of the cases. Relatively high off-diagonal cross-talk values were measured between 800 DL and DVB-T and between 1800 DL and DECT bands. These values would be expected, since there is a relatively small difference of 1 MHz (800 DL and DVB-T) and

< 1 MHz (DECT and 1800 DL) between the edges of the considered frequency bands, respectively, in comparison to the bandwidth of the considered frequency bands. The highest off-diagonal cross-talk values in these frequency bands were also observed for either the lowest or highest frequency in the studied bands, which indicates that signals can also be emitted close to the edge of a band in reality, the on-body cross-talk values presented in Table B1 (Appendix B) might be higher as well. Relatively high off-diagonal cross-talk values were also found in the ISM 5.8 band in Table B1, Appendix B. We also observed cross-talk in the on-body matrix in Table B1 (Appendix B) in the same frequency band, but with a lower magnitude.

4.3. Strengths, limitations and implications

This is the first microenvironmental exposure study to assess far-field RF-EMF exposures from multiple sources across different microenvironments using a pair of *on-body* calibrated exposimeters. Consequently, our measurements have taken into account body shielding by using frequency-band specific calibration factors or the averaged response of two exposimeters. This means the exposures levels reported in this study provide reduced measurement uncertainties related to body shielding and are corrected for the underestimation caused by the absorption of RF-EMF by the human body. Our study is also the first micro-environmental RF-EMF exposure study which evaluated the performance of the exposimeters by using cross-talk measurements, which can be used to interpret the data collected. Furthermore, we evaluated exposure in the 2.6 GHz, WiMaX 3.5 GHz, and ISM 5.8 GHz bands, which were not included in previous studies. Only one recent study (Ibrani et al., 2016), has included evaluation of personal exposures from WiMax 3.5 GHz and ISM 5.8 bands. The exposimeters used in our study are more sensitive than other available and commonly used exposimeters (Bhatt et al., 2016b). The results of this study also allow us to make a valid comparison of the exposure levels across microenvironments in Australia and Belgium, which are characterized by different infrastructure, geophysical, environmental and weather conditions. Therefore, the issue of measurements below the LODs is much less critical, which has been a major challenge in previous exposure assessments (Bolte and Eikelboom, 2012; Frei et al., 2009; Gajsek et al., 2013; Joseph et al., 2010; Juhász et al., 2011; Thomas et al., 2008; Urbinello et al., 2014b).

However, the study has the following limitations: i) we only involved one site/route per microenvironment and therefore our findings could only provide an estimate for microenvironmental exposure characterization, ii) not all measurements were repeated, iii) each measurement duration was only 15 min, iv) assessment of exposure variability involved only two measurements (15 min each), and v) many other sources of RF-EMF exposure in both countries (Australian Radiofrequency Spectrum Plan, 2013; Belgian Institute for Postal Services and Telecommunications, 2016; SpectrumMonitoring, 2016a, 2016b) could not be assessed due to the limitation of the measurement device. For instance, AM radio, which is a major source of environmental RF-EMF exposure in Melbourne (Henderson et al., 2014).

We have successfully performed personal far-field RF-EMF exposure assessment using on-body calibrated exposimeters. Therefore the approach contributes towards the development of improved exposure assessment methodology for epidemiological studies. Nevertheless, the application of multiple on-body calibrated exposimeters in epidemiological research may not always be the most rational approach. This is primarily because an on-body calibration is a resource intensive procedure, which is not achievable for large numbers of participants in epidemiological studies. In addition, it is not yet well understood how the results from a limited number of on-body calibrations for a small set of subjects can be translated into a general calibration factor useful for the whole population characterized with different body types (Bhatt et al., 2016a). However, it may still be useful to evaluate calibration factors for various body types, which could potentially be applied in exposure assessment for general populations.

5. Conclusions

We measured personal far-field RF-EMF exposure, frequency range 88 MHz to 5.8 GHz, in Australia and Belgium across various microenvironments using *on-body* calibrated exposimeters. Therefore, our study demonstrated that it was feasible to employ two exposimeters concurrently to estimate personal exposure minimizing the consequences of body shielding. Furthermore, our findings showed that the concurrent use of two on-body calibrated exposimeters provided the average exposure levels of 1.35 and 1.6 times higher in Australia and Belgium respectively, than those provided with a single non-on-body calibrated exposimeter. This implies that exposure assessment with the use of two on-body calibrated exposimeters has benefits over the use of a single non-on-body calibrated exposimeter and hence is recommended, if possible. Mobile phone base downlink exposures contributed the largest share to total exposures. Of 17 microenvironments compared, nine of them provided lower exposure levels in Melbourne (Australia) than the corresponding microenvironments in Ghent (Belgium). The personal exposures across urban microenvironments were lower than those in rural and suburban microenvironments. Similarly, exposure levels found across indoor microenvironments were lower than outdoors. Further studies are needed to provide more accurate exposure characterization considering multiple sites/routes per microenvironment.

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Appendix A

(See Table A1).

Table A1
Proportion of measured data (%) falling below the LODs of ExpoM-RFs across various microenvironments in Australia (n=19) and Belgium (n=19).

Microenvironments	Countries	ExpoM-RF IDs	FM	DVT-T	800 UL	800 DL	900 UL	900 DL	1800 UL	1800 DL	DECT	1900 UL	2100 DL	ISM 2.4	2600 UL	2600 DL	WiMax 3.5	ISM 5.8
Residential outdoor (urban)	Australia	40	73, 76	0, 0	75, 78	40, 49	0, 0	0, 0	68, 91	0, 0	0, 0	96, 99	0, 0	9, 19	99, 100	16, 7	99, 99	53, 81
		64	58, 68	4, 0	10, 37	31, 36	0, 0	0, 0	68, 89	0, 0	0, 0	96, 99	0, 0	0, 0	100, 100	16, 9	93, 97	63, 89
	Belgium	40	7, 0	0, 0	16, 8	93, 99	95, 91	0, 0	41, 36	0, 0	0, 0	99, 98	0, 0	0, 0	100, 100	100, 100	100, 98	54, 50
		64	3, 0	3, 0	0, 0	97, 96	91, 83	0, 0	95, 76	0, 0	6, 0	99, 98	0, 0	0, 0	100, 100	100, 100	100, 100	85, 8
Residential indoor (urban)	Australia	40	100, 100	99, 4	96, 97	99, 100	0, 0	0, 0	97, 99	0, 0	4, 7	99, 99	0, 0	9, 21	100, 100	0, 0	100, 100	100, 100
		64	100, 100	84, 40	72, 15	97, 99	0, 0	0, 0	97, 99	0, 0	19, 11	99, 99	0, 0	0, 0	100, 100	0, 0	100, 100	100, 100
	Belgium	40	14, 3	3, 0	20, 8	100, 32	96, 98	0, 0	94, 98	0, 0	24, 9	100, 100	0, 0	0, 0	100, 98	100, 100	100, 100	100, 100
		64	17, 1	23, 12	0, 0	100, 8	97, 98	0, 0	99, 98	0, 0	89, 18	100, 100	0, 0	0, 0	100, 100	100, 100	99, 100	99, 100
Office indoor (urban)	Australia	40	88, 98	38, 40	97, 100	83, 97	34, 45	0, 0	92, 69	2, 4	68, 48	33, 40	0, 0	7, 5	100, 100	87, 86	100, 100	100, 100
		64	99, 100	44, 44	80, 70	58, 46	7, 41	0, 0	95, 79	3, 13	80, 48	32, 45	0, 1	0, 0	100, 100	68, 48	100, 100	100, 100
	Belgium	40	94, 83	79, 64	18, 51	82, 66	58, 77	0, 0	76, 64	15, 26	23, 31	74, 66	6, 16	4, 8	85, 100	97, 100	100, 100	44, 71
		64	85, 86	100, 99	3, 3	81, 59	52, 76	0, 0	80, 70	18, 20	25, 29	74, 64	8, 16	0, 0	78, 100	96, 100	97, 100	68, 83
Park (urban)	Australia	40	82, 96	0, 0	55, 41	5, 0	0, 0	0, 0	92, 93	0, 0	0, 0	100, 99	0, 0	34, 19	100, 100	1, 1	99, 97	75, 62
		64	67, 90	0, 0	0, 10	0, 0	0, 0	0, 0	94, 96	0, 0	0, 0	99, 99	0, 0	0, 0	100, 100	0, 0	98, 95	94, 92
	Belgium	40	0, 0	0, 0	0, 0	99, 96	92, 92	0, 0	87, 85	0, 0	0, 0	99, 98	0, 0	35, 13	100, 100	100, 100	54, 21	94, 81
		64	1, 0	0, 0	0, 0	100, 98	90, 88	0, 0	93, 90	0, 0	6, 0	100, 99	0, 0	0, 0	100, 100	100, 100	34, 13	98, 93
City center	Australia	40	0, 0	0, 0	25, 47	0, 0	0, 0	0, 0	0, 0	0, 0	0, 0	30, 39	0, 0	0, 0	29, 71	0, 0	5, 17	0, 0
		64	0, 0	0, 0	0, 0	0, 0	0, 0	0, 0	0, 0	0, 0	0, 0	85, 84	0, 0	0, 0	1, 6	0, 0	2, 10	0, 0
	Belgium	40	0, 0	0, 0	0, 0	66, 90	57, 53	0, 0	17, 33	0, 0	0, 4	97, 92	0, 0	0, 1	100, 100	100, 100	89, 70	53, 89
		64	0, 0	0, 0	0, 0	67, 87	38, 33	0, 0	16, 40	0, 0	0, 3	97, 88	0, 0	0, 0	100, 100	100, 100	74, 38	64, 95
Library (urban)	Australia	40	98, 94	14, 13	100, 100	99, 99	1, 3	0, 0	92, 81	2, 0	13, 14	80, 77	0, 1	1, 7	100, 100	100, 100	100, 100	98, 94
		64	99, 96	88, 76	100, 100	69, 80	0, 0	0, 0	94, 91	4, 0	26, 42	80, 81	0, 0	0, 0	100, 100	100, 100	100, 100	99, 97
	[a]Belgium	40	0	0	0	99	96	0	84	0	0	97	0	0	100	100	2	67
		64	0	0	0	99	90	0	91	0	0	100	0	0	100	100	1	35
Shopping center (urban)	Australia	40	99, 98	73, 52	99, 99	60, 55	71, 35	0, 0	69, 27	66, 66	85, 90	68, 61	31, 43	0, 5	99, 100	79, 84	100, 100	100, 100
		64	99, 96	73, 60	98, 83	56, 40	64, 18	0, 0	71, 50	65, 65	82, 91	66, 60	32, 41	0, 0	98, 99	55, 59	100, 100	100, 100
	[a]Belgium	40	5	12	44	59	8	0	26	5	6	10	3	0	100	100	97	99
		64	11	54	5	44	5	0	33	7	8	6	4	0	100	100	97	100
Train station (urban)	Australia	40	85, 99	0, 0	100, 100	0, 10	0, 0	0, 0	8, 24	0, 0	0, 0	52, 56	0, 0	0, 0	94, 96	3, 0	100, 100	14, 29
		64	91, 91	0, 0	93, 91	0, 0	0, 0	0, 0	49, 43	0, 0	0, 0	48, 50	0, 0	0, 0	89, 99	0, 1	100, 100	48, 66
	[a]Belgium	40	1	1	56	77	13	0	31	1	17	46	0	9	98	100	81	77
		64	3	4	13	51	9	0	38	8	22	50	0	0	100	100	55	81
Tram station (urban)	Australia	40	84, 59	0, 0	31, 38	3, 2	0, 0	0, 0	71, 72	0, 0	0, 0	86, 90	0, 0	2, 1	100, 99	0, 0	100, 100	99, 100
		64	79, 48	0, 0	0, 0	0, 0	0, 0	0, 0	82, 80	0, 0	0, 0	90, 86	0, 0	0, 0	98, 96	0, 0	100, 100	100, 100
	[a]Belgium	40	0	0	0	100	77	0	64	0	0	100	0	97	100	100	0	7
		64	0	0	0	77	36	0	34	0	0	99	0	96	98	100	0	9
Bicycle (urban)	Australia	40	14, 27	0, 0	50, 32	4, 3	0, 0	0, 0	64, 65	0, 0	2, 1	86, 89	0, 0	9, 11	92, 97	3, 1	95, 93	67, 66
		64	15, 4	1, 8	21, 14	0, 1	0, 0	0, 0	75, 71	0, 0	4, 3	86, 90	0, 0	0, 0	93, 94	1, 0	97, 95	79, 76
	[a]Belgium	40	1	0	1	99	96	0	88	0	0	99	0	36	100	100	59	98
		64	0	1	0	95	85	0	85	0	0	96	0	0	100	100	30	94
Bicycle (rural/suburban)	[a]Belgium	40	95	78	97	18	97	0	100	55	93	100	2	88	100	100	100	100
		64	88	92	95	0	98	0	100	60	97	100	5	4	100	100	100	100
Bus (urban)	Australia	40	100, 54	7, 0	72, 88	54, 36	0, 0	0, 0	77, 97	0, 0	56, 24	21, 67	0, 0	34, 33	100, 100	100, 95	100, 100	84, 95
		64	99, 68	30, 0	56, 71	33, 12	0, 0	0, 0	95, 98	0, 0	60, 26	7, 66	1, 0	0, 0	100, 100	100, 91	99, 100	92, 98
	Belgium	40	0, 3	0, 14	6, 31	86, 100	77, 92	0, 0	70, 74	0, 16	4, 41	88, 3	0, 0	0, 66	100, 100	100, 100	70, 90	95, 100
		64	0, 13	0, 29	0, 4	84, 99	75, 92	0, 0	78, 75	0, 21	10, 49	87, 12	1, 0	0, 0	100, 100	100, 100	62, 89	98, 100
Car (urban/suburban)	Australia	40	72, 87	72, 75	100, 99	98, 98	74, 42	0, 0	99, 99	39, 33	85, 63	99, 100	28, 48	98, 99	100, 100	100, 100	100, 100	100, 100
		64	63, 87	91, 90	91, 83	94, 96	62, 25	0, 0	99, 99	48, 31	84, 65	99, 99	31, 50	0, 0	100, 100	100, 100	100, 100	100, 100

Table A1 (*continued*)

Microenvironments	Countries	ExpoM-RF IDs	FM	DVT-T	800 UL	800 DL	900 UL	900 DL	1800 UL	1800 DL	DECT	1900 UL	2100 DL	ISM 2.4	2600 UL	2600 DL	WiMax 3.5	ISM 5.8
	Belgium	40	3, 20	1, 0	18, 13	100, 99	92, 89	0, 0	86, 65	3, 0	11, 0	96, 100	0, 0	38, 38	100, 100	100, 100	71, 100	98, 91
		64	41, 19	3, 34	2, 0	97, 100	90, 91	0, 0	91, 69	4, 0	14, 1	97, 100	1, 0	0, 0	100, 100	100, 100	60, 99	99, 100
Car (rural/suburban)	[a]Belgium	40	100	63	99	52	97	0	100	60	65	100	32	32	84	100	100	100
		64	100	73	99	34	98	0	99	60	66	99	35	0	65	100	100	100
Tram (urban)	Australia	40	17, 25	0, 0	59, 52	44, 38	0, 0	0, 0	45, 14	0, 0	19, 22	49, 29	0, 0	2, 10	81, 85	0, 0	98, 99	81, 75
		64	13, 10	0, 0	17, 8	12, 0	0, 0	0, 0	54, 17	0, 0	22, 36	46, 26	0, 0	0, 0	73, 84	0, 0	98, 98	86, 84
	[a]Belgium	40	0	0	23	53	71	0	66	0	2	62	0	2	100	100	70	96
		64	0	0	0	40	68	0	73	0	2	69	0	0	100	100	96	97
Train	Australia	40	99, 100	12, 5	78, 80	46, 27	0, 0	0, 0	0, 19	14, 7	32, 26	1, 10	18, 3	0, 18	88, 98	78, 8	99, 100	70, 89
		64	99, 100	28, 22	21, 34	1, 12	0, 0	0, 0	3, 24	8, 7	27, 31	2, 10	16, 5	0, 0	74, 91	70, 73	99, 99	85, 97
	Belgium	40	78, 81	47, 73	53, 59	71, 60	70, 2	0, 0	94, 66	42, 51	58, 71	57, 3	22, 9	94, 43	100, 100	100, 100	96, 97	100, 84
		64	59, 83	56, 77	7, 10	68, 50	68, 1	0, 0	94, 62	41, 47	62, 77	59, 3	20, 14	0, 0	100, 92	100, 100	93, 94	100, 91
[a]Subway station/ride (urban)	Australia	40	24	95	98	63	2	0	94	12	8	58	96	47	100	100	100	97
		64	5	84	59	85	0	0	94	8	7	58	95	0	98	100	100	97
Residential outdoor (rural/ suburban)	Australia	40	28, 4	11, 6	100, 100	99, 100	11, 4	0, 0	100, 100	11, 1	56, 23	100, 99	0, 0	97, 81	100, 100	100, 100	100, 100	100, 100
		64	3, 15	46, 53	96, 100	89, 98	1, 0	0, 0	100, 100	11, 4	77, 34	100, 100	0, 1	0, 0	100, 100	100, 100	100, 100	100, 100
	Belgium	40	100, 100	100, 58	31, 16	99, 100	96, 99	0, 0	98, 100	43, 50	98, 98	100, 99	25, 16	42, 74	100, 100	98, 100	99, 100	99, 100
		64	99, 100	100, 99	0, 0	98, 100	98, 98	0, 0	98, 100	53, 55	99, 100	99, 100	34, 20	13, 0	99, 100	100, 100	99, 100	100, 100
Residential indoor (rural/ suburban)	[a]Australia	40	4	99	100	99	98	0	100	2	76	100	41	91	100	100	100	100
		64	15	100	99	100	72	0	100	7	100	100	63	0	100	100	100	100
	Belgium	40	100, 100	100, 99	100, 100	99, 100	92, 100	0, 0	100, 100	99, 100	99, 100	99, 100	100, 99	0, 0	100, 99	100, 100	100, 100	100, 100
		64	100, 100	100, 99	89, 59	99, 100	91, 99	4, 0	100, 100	99, 100	100, 99	99, 100	99, 100	0, 0	99, 100	100, 100	100, 100	100, 100
[a]Airport indoor	Australia	40	100	65	95	85	7	0	53	5	62	16	0	0	100	48	100	73
		64	100	67	78	67	4	0	54	2	61	16	0	0	95	41	100	89
	Belgium	40	100	94	100	100	22	0	1	0	23	9	0	0	100	100	100	83
		64	100	92	100	100	18	0	6	0	48	17	0	0	100	100	100	95
[a]Mountain/forest (rural)	Australia	40	100	91	100	100	100	0	100	100	100	100	100	100	99	100	100	100
		64	100	100	99	100	100	0	100	100	100	100	100	100	100	100	100	100

[a]Single measurement.

Appendix B

Calibration procedure

The calibration procedure consisted of two steps. In step one, the E_{inc} emitted by the transmitting antenna (T_X) was measured without the subject present. For this, measurements of E_{inc} were carried out along a vertical axis on the future assigned position of the subject in the measurement set-up using a Narda NBM-550 broadband field meter (Narda, Hauppauge, NY, USA). The (quadratic) E_{inc} values were then averaged over the height of the subject. This was repeated for two orthogonal polarizations of the T_X: parallel to the four walls of the chamber (V polarization) and parallel to the floor of the chamber (H polarization). This was also repeated for every center frequency of the 15 frequency bands (DVB-T and higher) that could be calibrated in the available chamber.

In step two, the subject equipped with the ExpoM-RF 64 took place on the rotational platform in the far field of the T_X (see Fig. 1a). The subject was rotated over 360° in azimuthal direction, while being exposed to the previously measured constant incident E_{inc}, which was V-polarized during a first rotation and then H-polarized. This rotation is executed in order to emulate an unknown orientation of the subject in an exposure situation (Thielens et al., 2013). During these rotations the T_X subsequently emitted each one of the central frequencies of the studied frequency bands, while the ExpoM-RF recorded the electric fields on the body (E_{body}). This resulted in 60 measurements of E_{body} per rotation (one each 6°) for two polarizations and 15 frequency bands.

The recorded E_{body} values were not the same as the incident fields (Thielens et al., 2015a), but rather provided a distribution depending on the angle of incidence and the incident polarization (Thielens et al., 2013, 2015b; Vanveerdeghem et al., 2015). Therefore, the ratio of E_{body} and E_{inc} was studied using the ExpoM-RF's response, $R = E_{body}/E_{inc}$, where $R > 1$ indicated an overestimation of E_{inc}, and $R < 1$ indicated an underestimation. R was determined in the post-processing of the calibration measurements, where a uniformly random angle of incidence and polarization was considered to determine the distribution of R. This distribution is characterized by its median value ($p_{50}(R)$) and its 50% prediction interval (PI_{50}):

$$PI_{50} = \frac{p_{75}(R)}{p_{25}(R)} \quad (1)$$

with $p_{75}(R)$ and $p_{25}(R)$ indicating the 75th and 25th percentiles of R, respectively. A small value of PI_{50} is desirable.

During the exposure assessment in the microenvironments, the ExpoM-RFs measured E_{body} values, which were used to estimate incident field strengths ($\hat{E}_{inc}$), using this response. In this study, we estimated $\hat{E}_{inc}$, using the median ($p_{50}(R)$):

$$\hat{E}_{inc} = \frac{E_{meas}}{p_{50}(R)} \quad (2)$$

with E_{meas}, the measured electric field strength. The uncertainty on this estimation is quantified using the PI_{50}.

Thielens et al. (2015a, (2015b) demonstrated that the PI_{50} value can be reduced, when multiple exposimeters are used simultaneously. Therefore, the subject was equipped with one ExpoM-RF on each hip, during the exposure assessment. Since only one ExpoM-RF was calibrated on the body, the same response was assumed for the second one, with this difference that the angular dependence was reflected with respect to the sagittal plane of the subject. The measured electric field values were averaged using a geometric average and were corrected for the influence of the body using Eq. (2).

During the calibration measurements, E_{body} values were registered in each frequency band, regardless of the emitted frequency. These measurements were used to determine the cross-talk of the ExpoM-RF. Cross-talk is defined as the ratio of the electric field strength value registered in a certain frequency band and the incident field strength in the band in which the electric field was actually emitted. Ideally, the cross-talk matrix equals the identity matrix: one on the main diagonal and zero off-diagonal. However, Thielens et al. (2015a) demonstrated that exposimeters can exhibit large off-diagonal cross-talk values. Cross-talk is problematic for personal exposure measurements, since it causes the registration of non-existent exposure values.

Following the on-body calibration, the ExpoM-RF 64 was also calibrated in free-space in the same anechoic chamber. Firstly, the ExpoM-RF 64 was placed vertically at a height of 1.5 m above the rotating platform supported by a polystyrene arm, while the T_X was oriented vertically as well. The T_X subsequently emitted a continuous wave at the lowest frequency, the central frequency, and the highest frequency in each of the 15 studied frequency bands, with a constant input power in the antenna. Simultaneously, the ExpoM-RF recorded electric field values (E_{expom}). These were then divided by the E_{inc} values measured in the previous on-body calibration in order to determine the free-space cross-talk and responses (see Table B2, Appendix B).

(See Tables B1 and B2).

Table B1
Median cross-talk values of ExpoM-RF 64 measured on the body of the subject.

Received															
Emitted	**DVB-T**	**800 UL**	**800 DL**	**900 UL**	**900 DL**	**1800 UL**	**1800 DL**	**DECT**	**1900 UL**	**2100 DL**	**ISM 2.4**	**2600 UL**	**2600 DL**	**WiMAX 3.5**	**ISM 5.8**
DVB-T	0.48	0.05	0.04	0.05	0.08	0.02	0.02	0.02	0.01	0.02	0.07	0.02	0.02	0.02	0.03
800 UL	0.03	0.58	0.01	0.01	0.02	0.01	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.01
800 DL	0.00	0.02	0.47	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.02
900 UL	0.00	0.01	0.01	0.53	0.01	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.01
900 DL	0.00	0.01	0.01	0.01	0.44	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.01
1800 UL	0.00	0.01	0.01	0.01	0.02	0.55	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.07
1800 DL	0.00	0.01	0.01	0.01	0.02	0.01	0.43	0.01	0.00	0.00	0.02	0.00	0.00	0.00	0.07
DECT	0.00	0.01	0.01	0.01	0.02	0.01	0.25	0.49	0.00	0.00	0.02	0.01	0.00	0.00	0.07
1900 UL	0.01	0.01	0.01	0.01	0.02	0.01	0.01	0.00	0.73	0.01	0.02	0.01	0.00	0.01	0.13
2100 DL	0.01	0.01	0.01	0.01	0.02	0.01	0.01	0.00	0.00	0.72	0.02	0.01	0.00	0.01	0.10
ISM 2.4	0.01	0.02	0.01	0.01	0.03	0.01	0.01	0.00	0.00	0.01	0.99	0.01	0.01	0.01	0.02
2600 UL	0.01	0.01	0.01	0.01	0.02	0.01	0.01	0.00	0.01	0.01	0.02	1.29	0.01	0.01	0.05
2600 DL	0.01	0.01	0.01	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.02	0.01	1.07	0.01	0.09
WiMAX 3.5	0.01	0.01	0.01	0.01	0.02	0.01	0.01	0.00	0.00	0.00	0.01	0.01	0.01	0.89	0.35
ISM 5.8	0.01	0.02	0.02	0.02	0.04	0.01	0.01	0.01	0.01	0.01	0.03	0.01	0.01	0.01	3.13

Table B2
Median cross-talk values of ExpoM-RF 64 measured off-body for a vertically polarized T_X antenna and a vertically placed ExpoM-RF 64 for the lower edge, the middle, and the upper edge of the listed frequency bands, respectively.

	Received														
Emitted	**DVB-T**	**800 UL**	**800 DL**	**900 UL**	**900 DL**	**1800 UL**	**1800 DL**	**DECT**	**1900 UL**	**2100 DL**	**ISM 2.4**	**2600 UL**	**2600 DL**	**WiMAX 3.5**	**ISM 5.8**
DVB-T	2.12–2.6–1.38	0.06–0.05–6.05	0.05–0.04–0.05	0.04–0.04–0.04	0.09–0.09–0.09	0.03–0.03–0.03	0.02–0.02–0.02	0.02–0.02–0.02	0.02–0.02–0.02	0.02–0.02–0.02	0.08–0.07–0.07	0.02–0.02–0.02	0.02–0.02–0.02	0.02–0.02–0.02	0.04–0.05–0.05
800 UL	0.35–0.15–0.01	1.62–1.81–1.6	0.01–0.01–0.02	0.01–0.01–0.01	0.02–0.02–0.02	0.01–0.01–0.01	0.01–0.01–0.01	0–0–0	0–0–0	0–0–0	0.02–0.02–0.02	0.01–0.01–0.01	0–0–0	0.01–0.01–.01	0.02–0.01–0.01
800 DL	0.01–0.01–0.01	0.03–0.04–0.02	1.2–1.43–1.14	0.01–0.01–0.01	0.02–0.02–0.02	0.01–0.01–0.01	0.01–0.01–0.01	0–0–0	0–0–0	0–0–0	0.02–0.01–0.01	0–0–0	0–0–0	0–0–0	0.01–0.01–0.02
900 UL	0–0–0	0.02–0.01–0.01	0.01–0.01–0.01	1.03–1.29–0.59	0.02–0.02–0.02	0.01–0–0.01	0–0–0	0–0–0	0–0–0	0–0–0	0.01–0.01–0.02	0–0–0	0–0–0	0–0–0	0.01–0.01–0.01
900 DL	0–0–0	0.01–0.01–0.01	0.01–0.01–0.01	0.01–0.01–0.01	1.2–0.67–0.32	0.01–0.01–0.01	0–0–0	0–0–0	0–0–0	0–0–0	0.02–0.02–0.02	0–0–0	0–0–0	0–0–0	0.01–0.01–0.02
1800 UL	0–0–0	0.01–0.01–0.01	0.01–0.01–0.01	0.01–0.01–0.01	0.02–0.02–0.02	0.99–1.25–1.01	0–0–0.05	0–0–0	0–0–0	0–0–0	0.01–0.01–0.01	0–0–0	0–0–0	0–0–0	0.12–0.17–0.18
1800 DL	0.01–0.01–0.01	0.01–0.01–0.01	0.01–0.01–0.01	0.01–0.01–0.01	0.03–0.02–0.02	0.01–0.01–0.01	0.88–0.97–0.8	0–0.02–1.04	0–0–0	0–0–0.01	0.03–0.05–0.04	0–0.01–0.01	0–0–0	0–0–0	0.19–0.17–0.07
DECT	0.01–0.01–0.01	0.01–0.01–0.01	0.01–0.01–0.01	0.01–0.01–0.01	0.02–0.02–0.02	0.01–0.01–0.01	0.85–0.53–0.06	1.1–1.06–1	0–0.01–0.08	0.01–0.01–0.01	0.04–0.03–0.02	0.01–0.01–0.01	0–0–0	0–0–0	0.07–0.15–0.11
1900 UL	0.01–0.01–0.01	0.01–0.01–0.01	0.01–0.01–0.01	0.01–0.01–0.01	0.03–0.02–0.02	0.01–0.01–0.01	0.01–0.01–0.01	0.01–0–0	1.2–0.98–0.71	0.01–0.01–0.01	0.02–0.02–0.02	0.01–0.01–0.01	0–0–0	0.01–0.01–0.01	0.1–0.2–0.22
2100 DL	0.01–0.01–0.01	0.01–0.01–0.01	0.01–0.01–0.01	0.01–0.01–0.01	0.02–0.02–0.02	0.01–0.01–0.01	0.01–0.01–0.01	0–0–0	0–0–0	1.34–1.2–0.89	0.03–0.03–0.03	0.01–0.01–0.01	0–0–0	0.01–0.01–0.01	0.18–0.17–0.13
ISM 2.4	0.01–0.01–0.01	0.02–0.01–0.01	0.01–0.01–0.01	0.01–0.01–0.01	0.02–0.02–0.02	0.01–0.01–0.01	0.01–0.01–0.01	0–0–0	0–0–0	0.01–0.01–0.01	1.18–1.26–0.51	0.01–0.01–0.36	0.01–0.01–0.01	0.01–0.01–0.01	0.03–0.03–0.04
2600 UL	0.01–0.01–0.01	0.02–0.01–0.01	0.01–0.01–0.01	0.01–0.01–0.01	0.02–0.02–0.02	0.01–0.01–0.01	0.01–0.01–0.01	0–0–0	0–0–0	0.01–0.01–0.01	0.02–0.02–0.02	0.61–1.02–1.26	0.01–0.01–0.01	0.01–0.01–0.01	0.03–0.04–0.04
2600 DL	0.01–0.01–0.01	0.02–0.01–0.01	0.01–0.01–0.01	0.01–0.01–0.01	0.03–0.03–0.03	0.01–0.01–0.01	0.01–0.01–0.01	0.01–0.01–0.01	0.01–0.01–0.01	0.01–0.01–0.01	0.02–0.02–0.02	0.01–0.01–0.01	0.77–0.64–0.79	0.01–0.01–0.01	0.06–0.06–0.07
WiMAX 3.5	0.01–0.01–0.01	0.01–0.01–0.01	0.01–0.01–0.01	0.01–0.01–0.01	0.02–0.02–0.02	0.01–0.01–0.01	0.01–0.01–0.01	0–0–0	0–0–0	0–0–0	0.02–0.01–0.01	0.01–0.01–0.01	0.01–0.01–0.01	0.7–0.38–0.2	0.19–0.14–0.05
ISM 5.8	0.01–0.01–0.01	0.02–0.02–0.02	0.02–0.02–0.02	0.02–0.02–0.02	0.04–0.04–0.04	0.01–0.01–0.01	0.01–0.01–0.01	0.01–0.01–0.01	0.01–0.01–0.01	0.01–0.01–0.01	0.03–0.03–0.03	0.01–0.01–0.01	0.01–0.01–0.01	0.01–0.01–0.01	1.3–2.17–1.23

References

Antenna Site Register, 2016. ⟨http://www.sites.bipt.be/index.php?language=EN⟩. (accessed 25.02.16).

Augner, C., Hacker, G.W., Oberfeld, G., Florian, M., Hitzl, W., Hutter, J., Pauser, G., 2010. Effects of exposure to GSM mobile phone base station signals on salivary cortisol, alpha-amylase, and immunoglobulin A. Biomed. Environ. Sci. 23, 199–207.

Australian Radiofrequency Spectrum Plan, 2013. Australian Communications and Media Authority. ⟨http://www.acma.gov.au/~/media/Spectrum%20Transformation%20and%20Government/Information/pdf/Australian%20Radiofrequency%20Spectrum%20Plan%202013.pdf⟩ (accessed 29.02.16).

Baan, R., Grosse, Y., Lauby-Secretan, B., El Ghissassi, F., Bouvard, V., Benbrahim-Tallaa, L., Guha, N., Islami, F., Galichet, L., Straif, K., 2011. Carcinogenicity of radiofrequency electromagnetic fields. Lancet Oncol. 12, 624–626.

Belgian Institute for Postal services and Telecommunications, 2016. ⟨http://www.bipt.be/en/operators/radio/frequency-management/frequency-plan/table⟩ (accessed 29.02.16).

Bhatt, C.R., Redmayne, M., Abramson, M.J., Benke, G., 2016b. Instruments to assess and measure personal and environmental radiofrequency-electromagnetic field exposures. Austral. Phys. Eng. Sci. Med. 39, 29–42.

Bhatt, C.R., Thielens, A., Redmayne, M., Abramson, M.J., Billah, B., Sim, M.R., Vermeulen, R., Martens, L., Joseph, W., Benke, G., 2016a. Measuring personal exposure from 900 MHz mobile phone base stations in australia and belgium using a novel personal distributed exposimeter. Environ. Int. 92–93, 388–397.

Blas, J., Lago, F.A., Fernández, P., Lorenzo, R.M., Abril, E.J., 2007. Potential exposure assessment errors associated with body-worn RFdosimeters. Bioelectromagnetics 28 (7), 573–576.

Bolte, J.F.B., 2016. Lessons learnt on biases and uncertainties in personal exposure measurement surveys of radiofrequency electromagnetic fields with exposimeters. Environ. Int 94, 724–735.

Bolte, J.F.B., Eikelboom, T., 2012. Personal radiofrequency electromagnetic field measurements in the Netherlands: Exposure level and variability for everyday activities, times of day and types of area. Environ. Int 48, 133–142.

Bolte, J.F.B., van der Zande, G., Kamer, J., 2011. Calibration and uncertainties in personal exposure measurements of radiofrequency electromagnetic fields. Bioelectromagnetics 32, 652–663.

Dürrenberger, G., Fröhlich, J., Röösli, M., Mattsson, M.O., 2014. EMF monitoring–concepts, activities, gaps and options. Int J. Environ. Res Public Health 11, 9460–9479.

Frei, P., Mohler, E., Neubauer, G., Theis, G., Burgi, A., Frohlich, J., Braun-Fahrlander, C., Bolte, J., Egger, M., Röösli, M., 2009. Temporal and spatial variability of personal exposure to radio frequency electromagnetic fields. Environ. Res 109, 779–785.

Neubauer, G., Cecil, S., Giczi, W., Petric, B., Preiner, P., Fröhlich, J., Röösli, M., 2008. Final Report on the project C2006-07: evaluation of the correlation between RF dosimeter reading and real human exposure ARC-IT-0218. ⟨http://www.emf.ethz.ch/archive/var/SB_Neubaue_pre25f.pdf⟩ (accessed 22.06.16).

Gajšek, P., Ravazzani, P., Wiart, J., Grellier, J., Samaras, T., Thuróczy, G., 2015. Electromagnetic field exposure assessment in Europe radiofrequency fields (10 MHz–6 GHz). J. Expo. Sci. Environ. Epidemiol. 25, 37–44.

Ganser, G.H., Hewett, P., 2010. An accurate substitution method for analyzing censored data. J. Occup. Environ. Hyg. 7, 233–244.

Henderson, S., Bangay, M., 2006. Survey of RF exposure levels from mobile telephone base stations in Australia. Bioelectromagnetics 27, 73–76.

Henderson, S., Tjong, L. Wijayasinghe, D., Survey of radiofrequency radiation levels across Melbourne. Proc. of the 39th Australasian Radiation Protection Society Conference, Hobart, 26–29 June 2014.

Hewett, P., Ganser, G.H., 2007. A comparison of several methods for analyzing censored data. Ann. Occup. Hyg. 51, 611–632.

Ibrani, M., Hamiti, E., Ahma, L., Shala, B., 2016. Assessment of personal radio frequency electromagnetic fieldexposure in specific indoor workplaces and possibleworst-case scenarios. Int. J. Electron. Commun. 70, 808–813. http://dx.doi.org/10.1016/j.aeue.2016.03.007.

ICNIRP, 1998. The International Commission on Non-ionizing Radiation Protection. Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 300 GHz). Health Phys. 74 (4), 494–522.

International Telecommunication Union, 2010. The evolution to 3G mobile – status report. ⟨https://www.itu.int/itunews/issue/2003/06/thirdgeneration.html⟩ (accessed 27.02.16).

Iskra, S., McKenzie, R.J., Cosic, I., 2011. Monte Carlo simulations of the electric field close to the body in realistic environments for application in personal radiofrequency dosimetry. Radiat. Prot. Dosim. 147, 517–527.

Iskra, S., McKenzie, R.J., Cosic, I., 2010. Factors influencing uncertainty in measurement of electric fields close to the body in personal RF dosimetry. Radiat. Prot. Dosim. 140 (1), 25–33.

Joseph, W., Verloock, L., 2010. Influence on mobile phone traffic on base station exposure of the general public. Health Phys. 99 (5), 631–638.

Joseph, W., Frei, P., Röösli, M., Thuróczy, G., Gajšek, P., Trcek, T., Bolte, J., Vermeeren, G., Mohler, E., Juhász, P., Finta, V., Martens, L., 2010. Comparison of personal radio frequency electromagnetic field exposure in different urban areas across Europe. Environ. Res. 110, 658–663.

Juhász, P., Bakos, J., Nagy, N., Jánossy, G., Finta, V., Thuróczy, G., 2011. RF personal exposimetry on employees of elementary schools, kindergartens and day nurseries as a proxy for child exposures. Prog. Biophys. Mol. Biol. 107, 449–455.

Kumar, S., 2004. Mobile communications: Global trends in the 21st century. Int J. Mob. Commun. 2, 67–86.

Manassas, A., Boursianis, A., Samaras, T., Sahalos, J.N., 2012. Continuous electromagnetic radiation monitoring in the environment: analysis of the results in Greece. Radiat. Prot. Dosim. 151 (3), 437–442.

Mann, S., 2010. Assessing personal exposures to environmental radiofrequency electromagnetic fields. Comptes Rendus Phys. 11, 541–555.

Najera, A., Gonzalez-Rubio, J., and Arribas E., 2016. Stastistical analysis of non-detects consideration in personal exposition to RF-EMF measurements [poster]. The BioEM Conference, Ghent, 5–10 June 2016.

Neubauer, G., Cecil, S., Giczi, W., Petric, B., Preiner, P., Fröhlich, J., Röösli, M., 2010. The association between exposure determined by radiofrequency personal exposimeters and human exposure: a simulation study. Bioelectromagnetics 31, 535–545.

OpenSignal, 2016. ⟨http://opensignal.com/⟩ (accessed 25.02.16).

Panagopoulos, D.J., Chavdoula, E.D., Margaritis, L.H., 2010. Bioeffects of mobile telephony radiation in relation to its intensity or distance from the antenna. Int J. Radiat. Biol. 86, 345–357.

Radiation Protection Standard, 2002. Maximum Exposure Levels to Radiofrequency Fields – 3 kHz to 300 GHz. Radiation Protection Series Publication No. 3. the Australian Radiation Protection and Nuclear Safety Agency, pp 1–128.

Radio Frequency National Site Archive, 2016. ⟨http://www.rfnsa.com.au/nsa/index.cgi?type=logout⟩ (accessed 25.02.16).

Roderíguez, B., Blas, J., Lorenzo, R.M., Fernández, P., Abril, E.J., 2011. Statistical perturbations in personal exposuremeterscaused by the human body in dynamic outdoor environments. Bioelectromagnetics 32, 209–217.

Röösli, M., Frei, P., Mohler, E., Braun-Fahrlander, C., Burgi, A., Frohlich, J., Neubauer, G., Theis, G., Egger, M., 2008. Statistical analysis of personal radiofrequency electromagnetic field measurements with nondetects. Bioelectromagnetics 29, 471–478.

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, R.C., Poulsen, A.H., Radon, K., Schuz, J., Thuroczy, G., Viel, J.F., Vrijheid, M., 2010. Conduct of a personal radiofrequency electromagnetic field measurement study: proposed study protocol. Environ. Health 9 (23), 1–14.

Rowley, J.T., Joyner, K.H., 2012. Comparative international analysis of radiofrequency exposure surveys of mobile communication radio base stations. J. Expo. Sci. Environ. Epidemiol. 22, 304–315.

Sagar, S., Struchen, B., Finta, V., Eeftens, M., Röösli, M., 2016. Use of portable exposimeters to monitor radiofrequency electromagnetic field exposure in the everyday environment. Environ. Res 150, 289–298. http://dx.doi.org/10.1016/j.envres.2016.06.020.

Spectrum Monitoring, 2016b. ⟨http://www.spectrummonitoring.com/frequencies/index.html#Belgium⟩. (accessed 18.03.16).

SpectrumMonitoring, 2016a. ⟨http://www.spectrummonitoring.com/frequencies/frequencies3.html#Australia⟩ (accessed 18.03.16).

The American Statistical Association, 2016. The ASA statement on statistical significance and P-values. February 5, 2016. Edited by Ronald L. Wasserstein, Executive Director.

Thielens, A., Agneessens, S., Verloock, L., Tanghe, E., Rogier, H., Martens, L., Joseph, W., 2015a. On-body calibration and processing for a combination of two radio-frequency personal exposimeters. Radiat. Prot. Dosim. 163, 58–69.

Thielens, A., De Clercq, H., Agneessens, S., Lecoutere, J., Verloock, L., Declercq, F., Vermeeren, G., Tanghe, E., Rogier, H., Puers, R., 2013. Personal distributed exposimeter for radio frequency exposure assessment in real environments. Bioelectromagnetics 34, 563–567.

Thielens, A., Agneessens, S., De Clercq, H., Lecoutere, J., Verloock, L., Tanghe, E., Aerts, S., Puers, R., Rogier, H., Martens, L., Joseph, W., 2015b. On-body calibration and measurements using a personal, distributed exposimeter for wireless fidelity. Health Phys. 108 (4), 407–418.

Thomas, S., Kühnlein, A., Heinrich, S., Praml, G., von Kries, R., Radon, K., 2008. Exposure to mobile telecommunication networks assessed using personal dosimetry and well-being in children and adolescents: the German MobilEe-study. Environ Health . http://dx.doi.org/10.1186/1476-069X-7-54.

Urbinello, D., Joseph, W., Verloock, L., Martens, L., Röösli, M., 2014a. Temporal trends of radio-frequency electromagnetic field (RF-EMF) exposure in everyday environments across European cities. Environ. Res. 134, 134–142.

Urbinello, D., Huss, A., Beekhuizen, J., Vermeulen, R., Röösli, M., 2014c. Use of portable exposure meters for comparing mobile phone base station radiation in different types of areas in the cities of Basel and Amsterdam. Sci. Total Environ. 468–469, 1028–1033.

Urbinello, D., Joseph, W., Huss, A., Verloock, L., Beekhuizen, J., Vermeulen, R., Martens, L., Röösli, M., 2014b. Radio-frequency electromagnetic field (RF-EMF) exposure levels in different European outdoor urban environments in comparison with regulatory limits. Environ. Int 68, 49–54.

van Deventer, E., van Rongen, E., Saunders, R., 2011. WHO research agenda for radiofrequency fields. Bioelectromagnetics 32, 417–421.

Vanveerdeghem, P., Vantorre, P., Thielens, A., Knockaert, J., Joseph, W., Rogier, H., 2015. Compact Personal Distributed Wearable Exposimeter. IEEE Sens. J. 15 (8), 4393–4401.

Vermeeren, G., Markakis, I., Goeminne, F., Samaras, T., Martens, L., Joseph, W., 2013. Spatial and temporal RF electromagnetic field exposure of children and adults in indoor micro environments in Belgium and Greece. Prog. Biophys. Mol. Biol. 113, 254–263.

Viel, J.F., Clerc, S., Barrera, C., Rymzhanova, R., Moissonnier, M., Hours, M., Cardis, E., 2009. Residential exposure to radiofrequency fields from mobile phone base stations, and broadcast transmitters: a population-based survey with personal meter. Occup. Environ. Med. 66, 550–556.

Chapter 5: RF-EMF Exposure in Kindergarten Children

Overview

This chapter involves the assessment of RF-EMF exposure in children at different kindergartens across Greater Melbourne, Australia. Therefore, this chapter broadens the range of the age groups covered for RF-EMF exposure assessment in the thesis. The exposures from different RF-EMF sources such as FM radio/television, mobile phone base stations (various frequencies of 2G, 3G and 4G) and Wi-Fi were measured in classrooms and playgrounds. In addition, the personal exposures were also reported. The chapter identifies the key sources of RF-EMF exposure to children in preschool settings and quantifies their respective contributions to total RF-EMF measured across 16 frequency bands (88 MHz-5.8 GHz). The total environmental exposures for kindergartens sited < 300 m from the nearest base station were compared to those sited > 300 m.

The chapter concludes that the three highest sources of environmental RF-EMF exposures were 900 MHz downlink, 2.1 GHz downlink, and 900 MHz uplink. Furthermore, the three highest personal exposure sources were 900 MHz downlink; 2.1 GHz downlink, 900 MHz uplink and 1.8 GHz downlink; and Frequency Modulation radio, Wi-Fi 2.4 GHz and Digital Video Broadcasting-Terrestrial. The exposures at kindergartens sited < 300 m from the nearest base station were higher compared to those sited > 300 m.

Declaration for Thesis Chapter 5

Manuscript: **Bhatt CR,** Billah B, Redmayne M, Abramson MJ, Benke G. Radiofrequency-electromagnetic field exposure in kindergarten children. *Journal of Exposure Science and Environmental Epidemiology,* 2016 October 19; doi: 10.1038/jes.2016.55.

Declaration by candidate

In the case of Chapter 5, the nature and extent of my contribution to the work was the following:

Nature of contribution	**Extent of contribution (%)**
Study concept and design, ethics approval, study funding, data collection, data analysis, manuscript preparation and editing, and revision of submitted manuscript	80%

The following co-authors contributed to the work. Where co-authors are students at Monash University, the extent of their contribution in percentage terms is stated:

Names	**Nature of contribution**
Baki Billah	Data analysis, data interpretation, manuscript editing, and revision of submitted manuscript
Mary Redmayne	Study concept and design, study funding, ethics approval, data collection, data analysis, manuscript editing, revision of submitted manuscript, and supervision
Michael J Abramson	Study concept and design, study funding, ethics approval, data interpretation, manuscript editing, revision of submitted manuscript, and supervision

Geza Benke	Study concept and design, study funding, ethics approval, data collection, data analysis, manuscript editing, revision of submitted manuscript, and supervision

The undersigned hereby certify that the above declaration correctly reflects the nature and extent of the candidate's and co-authors' contribution to this work.

Candidate's Signature	[redacted]	Date 28/04/2017

Main Supervisor's Signature	[redacted]	Date 28/04/2017

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ORIGINAL ARTICLE

Radiofrequency-electromagnetic field exposures in kindergarten children

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The aim of this study was to assess environmental and personal radiofrequency-electromagnetic field (RF-EMF) exposures in kindergarten children. Ten children and 20 kindergartens in Melbourne, Australia participated in personal and environmental exposure measurements, respectively. Order statistics of RF-EMF exposures were computed for 16 frequency bands between 88 MHz and 5.8 GHz. Of the 16 bands, the three highest sources of environmental RF-EMF exposures were: Global System for Mobile Communications (GSM) 900 MHz downlink (82 mV/m); Universal Mobile Telecommunications System (UMTS) 2100MHz downlink (51 mV/m); and GSM 900 MHz uplink (45 mV/m). Similarly, the three highest personal exposure sources were: GSM 900 MHz downlink (50 mV/m); UMTS 2100 MHz downlink, GSM 900 MHz uplink and GSM 1800 MHz downlink (20 mV/m); and Frequency Modulation radio, Wi-Fi 2.4 GHz and Digital Video Broadcasting-Terrestrial (10 mV/m). The median environmental exposures were: 179 mV/m (total all bands), 123 mV/m (total mobile phone base station downlinks), 46 mV/m (total mobile phone base station uplinks), and 16 mV/m (Wi-Fi 2.4 GHz). Similarly, the median personal exposures were: 81 mV/m (total all bands), 62 mV/m (total mobile phone base station downlinks), 21 mV/m (total mobile phone base station uplinks), and 9 mV/m (Wi-Fi 2.4 GHz). The measurements showed that environmental RF-EMF exposure levels exceeded the personal RF-EMF exposure levels at kindergartens.

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INTRODUCTION

People are being increasingly exposed to man-made sources of radiofrequency-electromagnetic fields (RF-EMFs). The RF-EMF exposure sources are broadly classified as near-field sources (mobile phones, iPad, tablets, laptops, and so on) and far-field sources (mobile phone base stations, Wi-Fi routers, radio/television broadcasting towers, and so on).[1] The exposure to RF-EMFs has been linked with the occurrence of possible adverse biological and health effects in humans, including in children.[2–5] However, several studies failed to detect statistically significant associations between RF-EMF exposure and health effects.[6–10] The International Agency for Research on Cancer has categorized RF-EMF as a possible human carcinogen (Group 2B).[11] The World Health Organization emphasizes the need of measuring RF-EMF personal exposures for performing human epidemiological studies.[12]

Several studies have been conducted to evaluate environmental and far-field personal RF-EMF exposures.[13–19] These studies have mainly focused on exposure assessment in adult populations. There is limited information on RF-EMF exposure levels among children and their relevant environments such as kindergartens and schools.[20,21] Some studies have estimated that absorption of RF-EMF from both near-[22,23] and far-field[24] sources is greater in children than adults. Age could be one of the parameters to influence differential biological effects of RF-EMF exposures.[25] A review by Foster and Chou[26] did not support that children absorb more RF-EMF from mobile phones than adults. However, this conclusion has been challenged.[23] In light of these scientific controversies, children's exposure to RF-EMF is a societal and public health concern worldwide.[27–30]

The purposes of this study were: (i) to assess environmental RF-EMF exposure levels in kindergartens and (ii) to evaluate personal RF-EMF exposure levels in the children attending kindergartens.

MATERIALS AND METHODS

The study included 20 kindergartens across Melbourne, Australia (Figure 1) to evaluate preschool children's environmental and personal RF-EMF exposures. The kindergartens were randomly selected from the list of kindergartens in metropolitan Melbourne accessed via the Australian online child care resource.[31] This study included kindergartens and crèches, located in Greater Melbourne region.

The study consisted of two components: (i) measuring environmental exposures and (ii) measuring personal exposures in selected children at the kindergartens. The kindergartens received an invitation letter along with an explanatory statement and consent form, inviting them to take part in the study. The directors of interested kindergartens provided written signed consent to allow the investigator to visit their kindergartens for RF-EMF exposure measurements.

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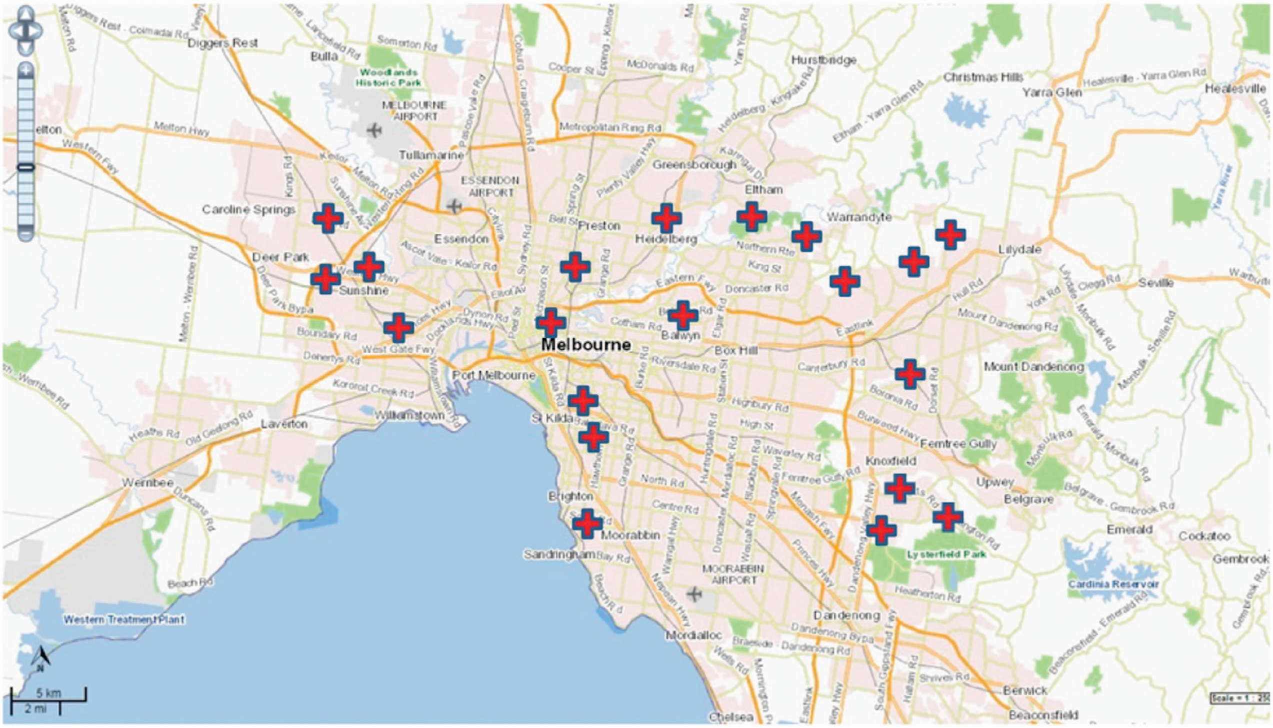

Figure 1. A map of Greater Melbourne showing approximate locations of participating kindergartens marked with red plus signs (source: http://maps.land.vic.gov.au/lassi/LassiUI.jsp).

Assessment of Environmental Exposure

The first author visited the kindergartens in the morning following receipt of consent from the kindergarten director. The director introduced him to staff and children explaining the purpose of his visit. Environmental RF-EMF exposures were measured at 10 different measurement points — five indoor points within one of the main classrooms and five outdoor points, in the playground of each kindergarten. The kindergarten classrooms and playground areas were of fairly square or rectangular shape. The measurement points were selected such that there was one point at each corner and one at the centre, of both the classroom and playground. For a kindergarten with more than one classroom, the measurements were performed in the largest classroom. The distance between each point was 5 and 10 m (on average) for the classroom and playground measurements, respectively. This standard measurement plan was followed consistently across all the kindergartens. The points were at least 1 m away from the walls (if any, for outdoor measurements) and windows in the case of indoor measurements. All measurements were performed between 0900 and 1300 hours (August–December 2015). A 6-min measurement was undertaken at each point providing 30 min of indoor and 30 min of outdoor measurements per kindergarten. The 6-min measurement period was based on the suggested exposure averaging period.[32]

Root mean square (RMS) environmental electric field strengths (E_{RMS} in V/m) were measured with an exposimeter, ExpoM-RF 64 (Fields at Work GmbH, Zürich, Switzerland), collecting data from the following 16 different frequency bands (88 MHz–5.8 GHz): Frequency Modulation (FM) radio, Digital Video Broadcasting-Terrestrial (DVB-T), Long-Term Evolution (LTE) 800 MHz uplink (UL) and downlink (DL), Global System For Mobile Communications (GSM) 900 MHz UL and DL, GSM 1800 MHz UL and DL, Digital-Enhanced Cordless Telecommunications (DECTs), Universal Mobile Telecommunications System (UMTS) 2100 MHz UL and DL, Industrial, Scientific and Medical (ISM) 2.4 GHz or Wi-Fi 2.4 GHz, LTE 2600 MHz UL and DL, Worldwide Interoperability for Microwave Access (WiMax) 3.5 GHz and ISM 5.8 GHz. The device had the following lower limits of detection (LOD): 20 mV/m (FM radio), 50 mV/m (ISM 5.8 GHz), 3 mV/m (LTE and WiMax), and 5 mV/m (the other frequencies).[1] The exposimeter was capable of assessing both environmental (ambient) and far-field personal RF-EMF exposure.[1,33] This meter did not measure other RF-EMF frequency bands that are used in Australia, such as AM radio, LTE 700 MHz, or WiMax 2.3 GHz, among others.[34]

The ExpoM-RF was affixed to a non-metallic tripod at a height of 1 m above ground level (Figures 2a and b). There was no physical obstruction between the ExpoM-RF and the closest window. The ExpoM-RF measurement system was moved from one point to another while performing spot measurements. The measurement interval of the ExpoM-RF was 3 s, and 120 data points were collected per measurement. A total of at least 1440 data signals were collected, comprising 720 each from indoor and outdoor environments.

Assessment of Personal Exposure

Personal exposure required a two-tier process for obtaining consent — first from the kindergarten and second from the parents who provided consent for their children to take part in the assessment. Following consent from the kindergarten director, each distributed invitation letters, explanatory letters, and consent forms to randomly selected parents of children aged 4–5 years requesting their child take part in the personal exposure measurements. Interested parents provided written consent to the director and/or the investigator. The personal exposure measurements were performed with the participating children on the day(s) following the environmental measurements, depending on the number of children participating and their attendance at kindergarten. A maximum of two children per kindergarten were measured in a single day. Some directors set a limit on the number of individuals who could participate, in which case selection was based on the earliest consent forms returned. If only one or two children were involved, we carried out the measurement in a single day. However, for kindergartens with more than two children involved, personal measurements were performed on different days having two children measured per day.

A total of 10 children, aged 4–5 years (6 boys and 4 girls), from five kindergartens took part in the personal measurements. The measurements were performed between 0830 and 1330 hours (October–December 2015). The ExpoM-RF 64 and ExpoM-RF 61 were used in the personal exposure measurements. The exposimeters were placed in small traveling bags, which were provided to participating children to wear around the chest for 3 h (Figure 2c). The investigator observed the children during the entire measurement while the children performed their usual kindergarten activities. A diary was used to gather information on activities undertaken by children and their locations (indoor or outdoor) during the measurements. If children felt tired or uncomfortable having the bag tied around

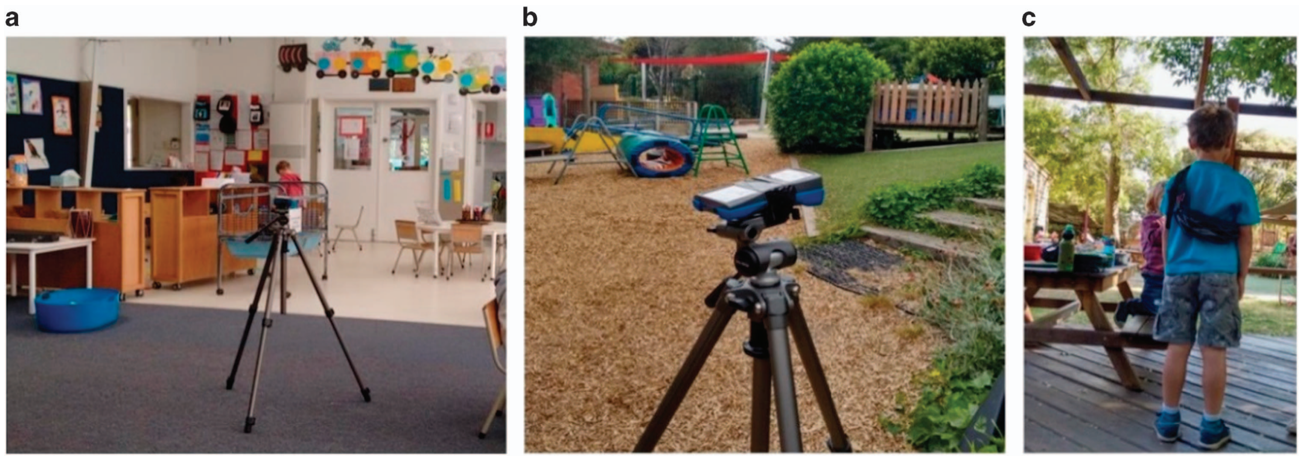

Figure 2. Measurement setups: an indoor (a), outdoor (b) (environmental) and personal (c) exposure measurements in a kindergarten (pictures taken with the permission of the kindergarten directors).

the chest during the entire measurement, the investigator adjusted the ExpoM-RF and tied it to the other side of the chest. Alternatively, the bag was also attached to the hips for some time. It ensured that children had the bag attached to their bodies throughout the measurement. Each personal measurement collected at least 3600 data points.

A short structured questionnaire was also used to collect information regarding the types and numbers of RF-EMF emitting devices in the kindergartens such as Wi-Fi router(s), cordless phone(s), microwave oven (s), and smart meters. Similarly, information on the presence of any radio/TV/mobile phone base station transmitter within 300 m from the kindergartens was also collected. The director of each kindergarten provided the information. In addition, the investigator also conducted a visual inspection of area to identify any nearby mobile phone base stations. The location and distance of nearest base station(s) was also verified with the information available online at the Australian Radio Frequency National Site Archive site.[35] No identifiable individual information about any kindergarten and child was collected.

The study received approval from the Monash University Human Research Ethics Committee. The investigator (CRB) obtained a Working with Children Check certificate.

Statistical Analysis

Analysis commenced with an assessment of the proportion of environmental and personal exposure data falling below the LODs of the respective frequency bands of the ExpoM-RFs. Shapiro–Wilk tests were performed on the untransformed and log-transformed data to evaluate normality. Visual inspection of histograms and the normal Q–Q plots was also carried out.

We used the substitution approach to derive summary statistics. All left censored (i.e. < the LODs) were replaced with their frequency-specific respective values of $LOD/\sqrt{2}$.[36,37] In the LTE 2600 MHz data, the values < LOD were replaced with zeros for the measurements of kindergarten when the measurement locations were found to be sited in areas not covered with LTE 2600 MHz network.[35] The censored values of 11 environmental and nine personal measurement data were substituted with zero in the LTE 2600 MHz DL and UL bands. In the ISM 5.8 GHz band, a majority of the data < LOD had considerable number of zero readings. The values < 20 mV/m were, in fact, automatically set to zero by the device as they were measured due to cross-talk. Therefore, we only replaced the non-zero values < LOD with $LOD/\sqrt{2}$.

Summary statistics for frequency-band-specific exposure levels were then computed using the data above the LODs and the substitute values for < LOD readings. This is an accepted method in practice in the field of environmental exposure assessment.[36–39] The exposure levels (E_{RMS}) were computed in terms of four exposure categories: (i) total exposure — RMS sum of the 16 frequency bands, (ii) mobile phone base station DLs exposure — RMS sum of all DLs (LTE 800 MHz, GSM 900 MHz, GSM 1800 MHz, UMTS 2100 MHz and LTE 2600 MHz), (iii) mobile phone base station UL exposure — RMS sum of all ULs (LTE 800 MHz, GSM 900 MHz, GSM 1800 MHz, UMTS 2100 MHz, and LTE 2600 MHz), and (iv) Wi-Fi 2.4 (ISM 2.4) exposure. Normality was tested for these groups of exposures.

Median exposure levels were computed to estimate environmental and personal RF-EMF exposures for each kindergarten and individual. Summary statistics (25th, 50th, 75th, and 99th percentiles) were then computed for all environmental and personal exposures from the median exposures of all kindergartens. Environmental analysis was undertaken for both indoor and outdoor environments; personal exposure analysis did not differentiate between indoor and outdoor environments. The median total, total DL, total UL, and Wi-Fi 2.4 GHz environmental exposures were calculated and compared for the kindergartens that were sited < 300 and > 300 m away from the nearest mobile phone base station.

Median total personal exposures ($n=10$) and median total environmental exposures (indoors and outdoors combined) ($n=5$) were compared for those kindergartens where both exposures were measured.

Wilcoxon's rank-sum tests were performed on the exposure data to evaluate the difference between: (i) indoor and outdoor environmental RF-EMF exposures, (ii) environmental exposures of kindergartens sited < 300 and > 300 m away from the mobile phone base stations, and (iii) personal and environmental total RF-EMF exposure levels. For all statistical tests, $P < 0.05$ (two sided) was considered as statistically significant. All data analysis was carried out using STATA ver13.1 (StataCorp, College Station, TX, USA).

RESULTS

Kindergarten and Exposure Data Characteristics

Of 20 kindergartens, 17 were community run not-for-profit, whereas 3 were private kindergartens. Fifteen kindergartens catered for children aged 3–5 years, three also catered for toddlers, and two catered for children aged 2.5–5 years.

All kindergartens had cordless phones (median = 2) in operation. All but two kindergartens had Wi-Fi routers (median = 1). Similarly, all kindergartens except two had microwave ovens (median = 1). Forty percent of kindergartens ($n=8$) reported "smart" meters installed in their building, whereas the remainder ($n=12$) were unaware of the presence of smart meters. Sixty percent of kindergartens ($n=12$) had at least one mobile phone base station at a distance of < 300 m. None of the kindergartens were within 300 m of a radio or TV station antenna.

In the case of personal exposure assessments, on average the participants spent nearly equal amounts of time in the indoor and outdoor environments. The mean indoor and outdoor times were 88 and 92 min, respectively. The children's key activities included playing in a group (indoor and outdoor), attending a classroom activity, and having morning tea and lunch. All participating children experienced only far-field RF-EMF exposure during the time they wore the ExpoM-RF device as none of them used a personal device such as a laptop, mobile phone, and so on over that period.

Some RF-EMF frequency bands had a substantial proportion of the results that showed values < LODs (Tables 1 and 2). However, these bands most likely had no nearby sources or had distant sources with low level of exposure. Most of the data measured above the LODs did not follow typical normal/lognormal distributions, rather the data followed inconsistent distributions.

Environmental and Personal Exposures

The environmental and personal exposure levels of all kindergartens and children are summarized for each measured frequency band (Table 3). The five highest median environmental RF-EMF exposures and their contributing sources were: GSM 900 MHz DL (82 mV/m); UMTS 2100 MHz DL (51 mV/m); GSM 900 MHz UL (45 mV/m); FM radio (29 mV/m); and DVB-T (18 mV/m). Similarly, the five highest sources of personal RF-EMF exposures were: GSM 900 MHz DL (50 mV/m); UMTS 2100 MHz DL; GSM 900 MHz UL and GSM 1800 MHz DL (20 mV/m); FM radio, Wi-Fi 2.4 GHz and DVB-T (10 mV/m), DECT (6 mV/m); and LTE 800 MHz DL (5 mV/m).

The summary statistics (25th, 50th, 75th, and 99th percentiles) of environmental exposure for all kindergartens and those located < 300 and > 300 m away from the nearest base station are summarized in terms of total, total DL, total UL, and Wi-Fi 2.4 GHz exposures (Table 4).

The median total exposures for total environment (indoor plus outdoor), indoor, and outdoor environments of all kindergartens was 179, 127, and 233 mV/m, respectively.

For the total, total DL, and total UL exposures, the median outdoor exposure levels were higher compared with the corresponding indoor exposure levels (*P*-values 0.01, 0.01, and 0.02 for total, total DL, and total UL, respectively). There was no statistically significant difference between the median indoor and outdoor environmental exposure levels of Wi-Fi 2.4 GHz ($P = 0.6$). The median exposure levels for those kindergartens < 300 m from the nearest mobile phone base station were significantly higher compared with the medians for those > 300 m away (*P*-values 0.01–0.003).

The personal exposures (25th, 50th, 75th, and 99th percentiles) of all children were: 47, 81, 154, and 255 mV/m (total); 33, 60, 129, and 213 mV/m (total DL); 8, 21, 47, and 81 mV/m (total UL); and 5, 9, 10, and 12 mV/m (Wi-Fi 2.4 GHz), respectively (data not shown).

Table 1. Proportion of measured environmental exposure data (%) falling below the LODs of ExpoM-RF across KGs ($n = 20$).

KG ID	*FM*	*DVB-T*	*LTE 800 DL*	*LTE 800 UL*	*GSM 900 UL*	*GSM 900 DL*	*GSM 1800 UL*	*GSM 1800 DL*	*DECT*	*UMTS UL*	*UMTS DL*	*ISM 2.4*	*LTE 2600 UL*	*LTE 2600 DL*	*WiMax 3.5*	*ISM 5.8*
1	52	51	100	50	0	0	98	0	77	99	0	0	96	100	100	100
2	22	0	4	33	0	0	98	0	39	96	0	0	98	69	100	100
3	49	4	3	63	0	0	90	0	50	100	0	0	98	100	100	99
4	0	0	18	0	0	0	100	0	0	100	0	0	83	0	94	85
5	48	0	56	96	0	0	94	0	0	99	0	0	87	100	100	94
6	70	83	100	96	0	0	98	1	76	91	0	3	99	100	100	100
7	21	50	59	48	0	0	99	0	25	99	0	0	95	100	100	100
8	5	50	100	100	3	0	100	41	100	100	0	0	95	100	100	100
9	18	0	52	11	0	0	100	0	0	100	0	0	76	100	100	89
10	1	10	100	27	0	0	98	24	97	100	6	0	94	95	100	99
11	0	16	53	96	0	0	99	0	0	100	0	0	65	100	100	96
12	53	0	0	24	0	0	72	0	0	100	0	0	80	100	99	73
13	60	0	10	6	0	0	90	0	0	100	0	0	99	100	92	81
14	1	3	100	42	0	0	100	2	99	100	0	0	99	100	100	100
15	0	0	100	39	0	0	100	0	33	100	0	26	97	100	100	100
16	69	0	100	63	0	0	99	0	6	100	0	33	100	100	100	100
17	47	0	50	0	0	0	69	0	0	100	0	0	91	92	74	66
18	63	100	56	35	0	0	100	0	19	100	0	0	88	100	100	100
19	29	66	58	50	2	0	99	7	45	100	4	0	85	100	100	100
20	0	45	2	86	0	0	98	0	73	98	12	0	95	100	100	100

Abbreviations: DECT, Digital-Enhanced Cordless Telecommunication; DL, downlink; DVB-T, Digital Video Broadcasting-Terrestrial; FM, Frequency Modulation; GSM, Global System For Mobile Communication; ISM, Industrial, Scientific and Medical; KG, kindergarten; LOD, limits of detection; LTE, Long-Term Evolution; UL, uplink; UMTS, Universal Mobile Telecommunications System; WiMax, Worldwide Interoperability for Microwave Access.

Table 2. Proportion of measured personal exposure data (%) falling below the LODs of ExpoM-RF across different kindergartens ($n = 5$).

Child IDs	*FM radio*	*DVB-T*	*LTE 800 DL*	*LTE 800 UL*	*GSM 900 UL*	*GSM 900 DL*	*GSM 1800 UL*	*GSM 1800 DL*	*DECT*	*UMTS UL*	*UMTS DL*	*ISM 2.4*	*LTE 2600 UL*	*LTE 2600 DL*	*WiMax 3.5*	*ISM 5.8*
1	9	17	18	34	0	0	99	0	5	100	0	0	98	100	100	98
2	99	0	100	55	0	0	99	0	1	100	0	72	99	100	100	86
3	100	37	37	48	0	0	99	0	18	100	0	0	96	100	100	99
4	99	98	44	99	34	0	99	72	98	100	0	0	99	100	100	100
5	98	24	100	99	74	0	99	88	99	100	0	49	100	100	100	100
6	99	99	71	96	50	0	99	87	97	100	0	0	99	100	100	100
7	78	0	72	14	0	0	100	0	1	100	0	0	99	100	100	100
8	53	0	100	82	5	0	100	16	100	100	0	69	100	100	100	100
9	47	75	48	69	3	0	100	26	100	100	1	2	100	100	100	99
10	99	12	22	24	0	0	100	0	12	100	0	0	99	99	100	96

Abbreviations: DECT, Digital-Enhanced Cordless Telecommunication; DL, downlink; DVB-T, Digital Video Broadcasting-Terrestrial; FM, Frequency Modulation; GSM, Global System For Mobile Communication; ISM, Industrial, Scientific and Medical; KG, kindergarten; LOD, limits of detection; LTE, Long-Term Evolution; UL, uplink; UMTS, Universal Mobile Telecommunications System; WiMax, Worldwide Interoperability for Microwave Access.

Table 3. Average combined indoor and outdoor environmental and personal exposure levels of all kindergartens ($n=20$) and children ($n=10$) across different RF-EMF frequency bands.

Frequency bands	*Environmental exposure levels (mV/m)*		*Personal exposure levels (mV/m)*	
	Median	*25th, 75th, 99th percentiles*	*Median*	*25th, 75th, 99th percentiles*
FM radio	29	14, 41, 120	10	10, 10, 21
DVB-T	18	5, 46, 87	10	3, 30, 46
LTE 800 MHz DL	3	3, 7, 19	5	3, 5, 6
LTE 800 MHz UL	5	3, 6, 18	3	3, 5, 7
GSM 900 MHz UL	45	19, 103, 236	20	6, 50, 81
GSM 900 MHz DL	82	32, 147, 352	50	30, 90, 194
GSM 1800 MHz UL	3	3, 3, 4	3	3, 3, 3
GSM 1800 MHz DL	39	16, 104, 165	20	3,50, 74
DECT	7	3, 22, 52	6	3, 10, 16
UMTS 2100 MHz UL	2	2, 2, 2	2	2, 2, 2
UMTS 2100 MHz DL	51	13, 99, 151	20	10, 40, 80
ISM 2.4 GHz	16	10, 22, 29	10	5, 10, 12
LTE 2600 MHz UL	0	0, 2, 2	0	0, 0, 2
LTE 2600 MHz DL	0	0, 2, 5	0	0, 0, 2
WiMax 3.5 GHz	2	2, 2, 2	2	2, 2, 2
ISM 5.8 GHz	0	0, 35, 35	0	0, 30, 40
[a]Total	179	75, 269, 431	70	40, 150, 255

Abbreviations: DECT, Digital-Enhanced Cordless Telecommunications; DL, downlink; DVB-T, Digital Video Broadcasting-Terrestrial; E_{RMS}, root mean square environmental electric field strength; GSM, Global System for Mobile Communications; ISM, Industrial, Scientific and Medical; LTE, Long-Term Evolution; RF-EMF, radiofrequency-electromagnetic field; UL, uplink; UMTS, Universal Mobile Telecommunications System; WiMAX, Worldwide Interoperability for Microwave Access. [a]Total exposure is the root mean square sum of the E_{RMS} from all enlisted frequency bands.

Table 4. Environmental exposure levels of the kindergartens ($n=20$) in terms of total, total downlink, total uplink, and Wi-Fi 2.4 GHz exposures.

Environments	*Total exposure (mV/m)*		*Total downlink exposure (mV/m)*		*Total uplink exposure (mV/m)*		*Wi-Fi 2.4 GHz exposure (mV/m)*	
	Median	*25th, 75th, 99th percentiles*	*Median*	*25th, 75th, 99th percentiles*	*Median*	*25th,75th, 99th percentiles*	*Median*	*25th,75th, 99th percentiles*
Total environment	179	75, 268, 431	123	44, 230, 388	46	20, 104, 236	16	9, 22, 29
Indoor environment	127	52, 185, 217	66	25, 138, 191	25	14, 67, 139	20	11, 22, 31
Outdoor environment	233	92, 393, 913	172	60, 306, 797	63	28, 157, 431	19	8, 24, 29
< 300 m away from the nearest base station								
Total environment[a]	258	159, 348, 431	221	91, 281, 388	93	37, 126, 237	15	10, 24, 29
Indoor environment[a]	168	120, 203, 217	130	60, 169, 192	54	24, 82, 139	19	11, 23, 31
Outdoor environment[a]	357	210, 458, 913	298	159, 412, 797	119	56, 244, 431	21	8, 26, 29
> 300 m away from the nearest base station								
Total environment[b]	75	63, 137, 211	49	30, 74, 168	20	19, 39, 94	18	9, 22, 23
Indoor environment[b]	52	44, 102, 163	27	22, 37, 97	14	10, 21, 42	20	13, 22, 25
Outdoor environment[b]	92	71, 133, 281	68	34, 86, 215	28	24, 52, 172	14	7, 22, 24

[a]Number of kindergartens $n=12$. [b]Number of kindergartens $n=8$; median exposure levels for kindergartens <300 m from the nearest base station were significantly higher compared with the medians for those >300 m away (P-values 0.01–0.003).

The median total, total DL, total UL, and Wi-Fi 2.4 GHz personal exposures for individual children are shown in Figure 3. Furthermore, Table 5 summarizes total personal exposures of children and environmental exposures at their associated kindergartens. All kindergartens that were involved in children's personal exposure measurements had Wi-Fi routers. Median total personal exposures for all children were lower compared with their median total environmental exposures ($P<0.001$ for all cases and $P=0.003$ for child 2 and kindergarten 1). Children 1, 2, and 3 belonged to kindergarten 1, IDs 4, 5, and 6 belonged to kindergarten 2. Similarly, child IDs 8 and 9 belonged to kindergarten 4 and child IDs 7 and 10 belonged to kindergartens 3 and 5, respectively. Children 1, 2, 3, 7, and 10 belonged to the kindergartens sited <300 m from the nearest base station, whereas the rest of the children belonged to kindergartens >300 m away.

DISCUSSION

This study presents the first findings on total environmental (indoor and outdoor) and far-field personal RF-EMF exposures in kindergarten children. The exposure levels found were well below the reference levels ($<1\%$) for the general public as provided in the guidelines of the International Commission on Non-Ionizing Radiation Protection,[32] and the Australian Radiation Protection

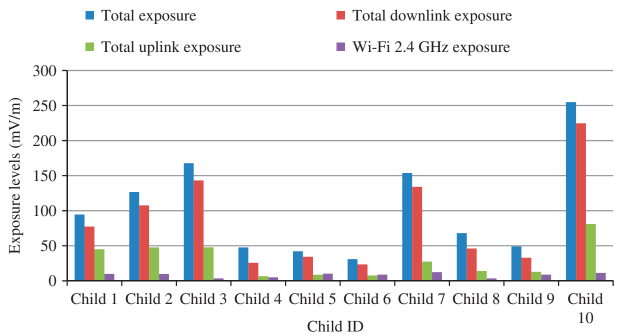

Figure 3. Median personal exposures of children ($n = 10$) and their total, total downlink, total uplink and Wi-Fi 2.4 GHz exposures.

Table 5. A comparison of personal and environmental total RF-EMF exposure levels (mV/m).

Child IDs	*KG IDs*[a]	*Personal exposure (mV/m)*		*Environmental exposure (mV/m)*	
		Median	*25th, 75th, 99th percentiles*	*Median*	*25th, 75th, 99th percentiles*
Child 1	1	126	92, 198, 556	211	112, 279, 650
Child 2		167	135, 233, 586		
Child 3		94	72, 135, 282		
Child 4	2	47	43, 55, 76	72	45, 91,115
Child 5		42	29, 52, 86		
Child 6		31	27, 40, 79		
Child 7	3	154	126, 184, 342	251	158, 353, 583
Child 8	4	68	55, 82, 139	147	118, 178, 209
Child 9		49	34, 65, 129		
Child 10	5	255	115, 459, 1128	412	196, 923, 2927

Abbreviations: KG, kindergarten; RF-EMF, radiofrequency-electromagnetic field. [a]KGs 1, 3, and 5 were sited < 300 m away from the nearest base station; median total personal exposures were < median total environmental exposures ($P < 0.001$ for all, and $P = 0.003$ for child 2, KG 1).

and Nuclear Safety Agency (ARPANSA).[40] It should be noted that in the context of standards and guidelines, the RF-EMF exposure limits are frequency range-dependent.[32,40] For compliance purposes, the measured frequency-band-specific environmental and personal exposures (99th percentile values) in terms of percentage of the ARPANSA reference levels are as follows: 0.88% (environmental) and 0.15% (personal) (FM radio), 0.25% (environmental), and 0.13% (personal) (DVB-T), 0.05% (environmental) and 0.01% (personal) (LTE 800 MHz DL), 0.04% (environmental), and 0.01% (personal) (LTE 800 MHz UL), 0.57% (environmental) and 0.20% (personal) (GSM 900 MHz UL), 0.83% (environmental) and 0.46% (personal) (GSM 900 MHz DL), 0.007% (environmental) and 0.005% (personal) (GSM 1800 MHz UL), 0.28 % (environmental) and 0.13 % (personal) (GSM 1800 MHz DL), 0.09% (environmental) and 0.03% (personal) (DECT), 0.003% (environmental and personal) (UMTS 2100 MHz UL), 0.24% (environmental) and 0.13% (personal) (UMTS 2100 MHz DL), 0.05% (environmental) and 0.02% (personal) (ISM 2.4 GHz), 0.003% (environmental and personal) (LTE 2600 MHz UL and WiMax 3.5 GHz), 0.008% (environmental) and 0.003% (personal) (LTE 2600 MHz DL), and 0.06% (environmental and personal) (ISM 5.8 GHz).The total, total DL, and total UL exposures provided in our paper may be relevant when comparing these exposures and those reported elsewhere.[13,18]

The exposure from mobile phone base stations was observed to be the largest source of environmental and far-field personal exposures. This finding is in line with previous studies that identified mobile phone base stations to be a major source of RF-EMF exposure.[13–15,20,21,41] Of mobile phone base station exposures, GSM 900 MHz DL contributed the highest share of total exposure. Similar findings have been reported elsewhere in the contexts of kindergartens and crèches.[20,21] The results of the indoor environmental RF-EMF levels in our study can be compared to crèche and school measurements performed in Belgium and Greece.[20] The average total and frequency-band-specific RF-EMF exposures in the schools and crèche in Belgium and in schools in Greece were higher compared with the median corresponding exposure levels found in our study.

Similarly, personal exposures of the kindergarten staff reported in Hungary were higher compared with the personal exposure of kindergarten children found in our study.[21] It is likely that staff had other RF-EMF sources, such as personal mobile handsets, which were likely to affect measured personal RF-EMF exposures.[19] In general, mobile phone base station 900 MHz DL exposure in Australia was lower compared with that in Belgium.[42] The present study also found personal exposures of children to be lower compared with their environmental exposures. This could be largely due to body shielding, as described in literature.[43] Our finding suggests that environmental exposure may not be a good proxy for personal exposure in kindergartens.

The higher levels of total environmental exposures at kindergartens located < 300 m from the nearest base station is likely to be due to RF-EMF exposure from the base station. Similarly, personal exposure for children attending kindergartens sited < 300 m from the nearest base station were higher compared with those children attending kindergartens > 300 away. The maxima of RF-EMF exposure lie within the distance between 50 and 300 m from the base station, if we neglect interference from the objects in RF-EMF beam path.[44]

Wi-Fi contributed an insignificant component of the overall environmental and personal RF-EMF exposures compared with other RF-EMF sources, particularly mobile phone base stations. In these preschool settings, the base station associated exposures were also observed to be higher compared with Wi-Fi 2.4 GHz exposure in indoor environments. Wi-Fi exposure was detected in all kindergartens, including those that did not have a Wi-Fi router. In the latter instance, Wi-Fi signals are likely to have emanated from nearby buildings. Although some cities now offer free outdoor Wi-Fi, this did not apply to the areas included in this study. It should be borne in mind that personal Wi-Fi exposure would increase if a Wi-Fi-enabled device was being used or carried. Generally, indoor Wi-Fi exposure levels are expected to be higher compared with the outdoor Wi-Fi exposure levels.[45] Nevertheless, the similar indoor and outdoor Wi-Fi exposures observed in our study may be attributed to the likely contribution from mobile phone base station exposure emitted at 2.3 GHz band (4G mobile phone frequency used by one of the network providers in Melbourne), which could have been measured at the Wi-Fi 2.4 GHz due to cross-talk.

Earlier studies of personal RF-EMF exposure of young children have been challenging owing to the lack of adequate compliance among children to follow measurement protocols, possible damage to (expensive) expositmeters, and size of the exposimeter that could discourage children from wearing it for an entire day.[21] Furthermore, response rates from kindergarten staff and parents were low. Ideally, measurement duration of at least 24 h would be optimal for personal RF-EMF measurements in adult humans.[46] However, this could not be met in our case as none of the kindergartens/parents provided consent when we initially approached 75 kindergartens proposing measurement duration of 24 h. Therefore, we chose 3 h measurement duration in this study to enable it to be carried out during a single session. This also allowed us to take an accurate diary of location (indoors or outdoors) throughout the period. Other kindergartens declined to take part because staff and parents of the children were concerned about the prospect of having an external adult in the kindergarten facility for security reasons, and because of the anxiety of kindergarten staff regarding the possibility of high exposures and this raising subsequent potential health concerns. Two children, whose parents initially consented eventually, decided not take part because the exposimeter was causing discomfort when it was being fitted.

Some frequency bands in this study showed high censoring, depending upon the band and site of measurements. Various approaches are available to deal with the left censored environmental data: substitution, log-probit regression/robust regression on order statistics (ROS), maximum-likelihood estimation methods and Kaplan–Meier methods.[36,37] The three common substitution methods in practice are substitution by LOD, LOD/2, and LOD/$\sqrt{2}$.[36,37] The performance of these methods has been evaluated using simulations on lognormal data and it was found that LOD/$\sqrt{2}$ substitution method provided slightly positively biased means and negatively biased 95th percentiles, yet comparable results compared with the other advanced approaches.[37] Furthermore, the evaluation of ROS and substitution (i.e. LOD) methods for RF-EMF exposure generally provided higher values of frequency-band-specific summary statistics of exposures (means, medians, 25th, 75th, and 95th percentiles) compared with the former method.[47] The more sensitive LODs of the exposimeters used in the present study resulted in far fewer censored data than eventuated from using earlier exposimeters.[1]

This is the first study to investigate kindergarten children's environmental and personal RF-EMF exposures. Therefore, the study provides a proof of concept to perform RF-EMF exposure assessment in young children for future RF-EMF epidemiological studies. In turn, our findings have implications for the design of larger studies and improving RF-EMF-related policies in Australia and worldwide. However, our study has the limitation that the exposures from some RF-EMF frequency bands, including AM radio,[34,48] are not measured. Furthermore, we observed a low response rate for personal exposure assessment.

In conclusion, this study provides evidence to support that of the 16 frequency bands measured the mobile phone base station DL exposure of GSM 900 MHz is the largest contributor to the total environmental and personal RF-EMF exposures in kindergartens in Melbourne. Wi-Fi exposure was found to be very low compared with mobile phone base station exposure. Environmental exposure levels at kindergartens located <300 m away from the nearest base station were higher compared with those located >300 m. The measurements suggested that the personal RF-EMF exposure levels were lower compared with the environmental RF-EMF levels at kindergartens.

CONFLICT OF INTEREST

Michael J. Abramson holds a small parcel of shares in Telstra, which operates a mobile telephone network in Australia. The other authors declare no conflict of interest.

REFERENCES

1 Bhatt CR, Redmayne M, Abramson MJ, Benke G. Instruments to assess and measure personal and environmental radiofrequency-electromagnetic field exposures. *Australas Phys Eng Sci Med* 2016; **39**: 29–42.
2 Interphone Study Group. Brain tumour risk in relation to mobile telephone use: results of the INTERPHONE international case–control study. *Int J Epidemiol* 2010; **39**: 675–694.
3 Abramson MJ, Benke GP, Dimitriadis C, Inyang IO, Sim MR, Wolfe RS *et al.* Mobile telephone use is associated with changes in cognitive function in young adolescents. *Bioelectromagnetics* 2009; **30**: 678–686.
4 Schoeni A, Roser K, Röösli M. Memory performance, wireless communication and exposure to radiofrequency electromagnetic fields: a prospective cohort study in adolescents. *Environ Int* 2015; **85**: 343–351.
5 Miyakoshi J. Cellular biology aspects of mobile phone radiation. In: Lin JC (ed). *Advances in Electromagnetic Field in Living Systems: Health Effects of Cell Phone Radiation*, vol 5. Springer: New York, NY, USA, 2009, pp 1–33.
6 Benson VS, Pirie K, Schüz J, Reeves GK, Beral V, Green J. Mobile phone use and risk of brain neoplasms and other cancers: prospective study. *Int J Epidemiol* 2013; **42**: 792–802.
7 Frei P, Poulsen AH, Johansen C, Olsen JH, Steding-Jessen M, Schüz J. Use of mobile phones and risk of brain tumours: update of Danish cohort study. *BMJ* 2011; **343**: d6387.
8 Thomas S, Benke G, Dimitriadis C, Inyang I, Sim MR, Wolfe R *et al.* Use of mobile phones and changes in cognitive function in adolescents. *Occup Environ Med* 2010; **67**: 861–866.
9 Valentini E, Ferrara M, Presaghi F, De Gennaro L, Curcio G. Republished review: systematic review and meta-analysis of psychomotor effects of mobile phone electromagnetic fields. *Postgrad Med J* 2011; **87**: 643–651.
10 Guxens M, van, Eijsden M, Vermeulen R, Loomans E, Vrijkotte TGM, Komhout H *et al.* Maternal cell phone and cordless phone use during pregnancy and behaviour problems in 5-year-old children. *J Epidemiol Community Health* 2013; **67**: 432–438.
11 Baan R, Grosse Y, Lauby-Secretan B, El Ghissassi F, Bouvard V, Benbrahim-Tallaa L *et al.* Carcinogenicity of radiofrequency electromagnetic fields. *Lancet Oncol* 2011; **12**: 624–626.
12 van Deventer E, van Rongen E, Saunders R. WHO research agenda for radiofrequency fields. *Bioelectromagnetics* 2011; **32**: 417–421.
13 Bolte JFB, Eikelboom T. Personal radiofrequency electromagnetic field measurements in the Netherlands: exposure level and variability for everyday activities, times of day and types of area. *Environ Int* 2012; **48**: 133–142.
14 Frei P, Mohler E, Neubauer G, Theis G, Burgi A, Frohlich J *et al.* Temporal and spatial variability of personal exposure to radio frequency electromagnetic fields. *Environ Res* 2009; **109**: 779–785.
15 Gajsek P, Ravazzani P, Wiart J, Grellier J, Samaras T, Thuroczy G. Electromagnetic field exposure assessment in Europe radiofrequency fields (10 MHz–6 GHz). *J Expo Sci Environ Epidemiol* 2013; **25**: 37–44.
16 Joseph W, Frei P, Röösli M, Thuróczy G, Gajsek P, Trcek T *et al.* Comparison of personal radio frequency electromagnetic field exposure in different urban areas across Europe. *Environ Res* 2010; **110**: 658–663.
17 Urbinello D, Joseph W, Huss A, Verloock L, Beekhuizen J, Vermeulen R *et al.* Radio-frequency electromagnetic field (RF-EMF) exposure levels in different European outdoor urban environments in comparison with regulatory limits. *Environ Int* 2014; **68c**: 49–54.
18 Urbinello D, Huss A, Beekhuizen J, Vermeulen R, Röösli M. Use of portable exposure meters for comparing mobile phone base station radiation in different types of areas in the cities of Basel and Amsterdam. *Sci Total Environ* 2014; **468–469**: 1028–103319.
19 Urbinello D, Röösli M. Impact of one's own mobile phone in stand-by mode on personal radiofrequency electromagnetic field exposure. *J Expo Sci Environ Epidemiol* 2013; **23**: 545–548.
20 Vermeeren G, Markakis I, Goeminne F, Samaras T, Martens L, Joseph W. Spatial and temporal RF electromagnetic field exposure of children and adults in indoor micro environments in Belgium and Greece. *Prog Biophys Mol Biol* 2013; **113**: 254–263.
21 Juhász P, Bakos J, Nagy N, Janossy G, Finta V, Thuroczy G. RF personal exposimetry on employees of elementary schools, kindergartens and day nurseries as a proxy for child exposures. *Prog Biophys Mol Biol* 2011; **107**: 449–455.
22 Gandhi OP. Yes the children are more exposed to radiofrequency energy from mobile telephones than adults. *IEEE Access* 2015; **3**: 985–988.
23 Morris RD, Morgan LL, Davis D. Children absorb higher doses of radio frequency electromagnetic radiation from mobile phones than adults. *IEEE Access* 2015; **3**: 2379–2387.
24 Joseph W, Frei P, Röösli M, Vermeeren G, Bolte J, Thuroczy G *et al.* Between-country comparison of whole-body SAR from personal exposure data in Urban areas. *Bioelectromagnetics* 2012; **33**: 682–694.
25 Redmayne M, Johansson O. Radiofrequency exposure in young and old: different sensitivities in light of age-relevant natural differences. *Rev Environ Health* 2015; **30**: 323–335.
26 Foster KR, Chou C-K. Are children more exposed to radio frequency energy from mobile phones than adults? *IEEE Access* 2014; **2**: 1497–1509.
27 Chapman S, Wutzke S. Not in our back yard: media coverage of community opposition to mobile phone towers — an application of Sandman's outrage model of risk perception. *Aust N Z J Public Health* 1997; **21**: 614–620.
28 Burgess A. Comparing national responses to perceived health risks from mobile phone masts. *Health Risk Soc* 2002; **4**: 175–188.

29 Redmayne M. International policy and advisory response regarding children's exposure to radio frequency electromagnetic fields (RF-EMF). *Electromagn Biol Med* 2016; **35**: 176–185.
30 Calvente I, Pérez-Lobato R, Núñez MI, Ramos R, Guxens M, Villalba J *et al.* Does exposure to environmental radiofrequency electromagnetic fields cause cognitive and behavioral effects in 10-year-old boys? *Bioelectromagnetics* 2016; **37**: 25–36.
31 Care for kids. Available at: https://www.careforkids.com.au/ (last accessed 14 February 2015).
32 ICNIRP. ICNIRP guidelines for limiting exposure to time-varying electric, magnetic and electromagnetic fields (up to 300 GHz). *Health Phys* 1998; **74**: 494–522.
33 Roser K, Schoeni A, Bürgi A, Röösli M. Development of an RF-EMF exposure surrogate for epidemiologic research. *Int J Environ Res Public Health* 2015; **12**: 5634–5656.
34 Australian Radiofrequency Spectrum Plan 2013. Available at: http://www.acma.gov.au/~/media/Spectrum%20Transformation%20and%20Government/Information/pdf/Australian%20Radiofrequency%20Spectrum%20Plan%202013.pdf (last accessed 17 February 2016).
35 Radio Frequency National Site Archive. Available at: http://www.rfnsa.com.au/nsa/index.cgi (last accessed 12 January 2016).
36 Ganser GH, Hewett P. An accurate substitution method for analyzing censored data. *J Occup Environ Hyg* 2010; **7**: 233–244.
37 Hewett P, Ganser GH. A comparison of several methods for analyzing censored data. *Ann Occup Hyg* 2007; **51**: 611–632.
38 Tekindal MA, Erdoğan BD, Yavuz Y. Evaluating left-censored data through substitution, parametric, semi-parametric, and nonparametric methods: a simulation study. *Interdiscip Sci* 2015 (doi:10.1007/s12539-015-0132-9).
39 Huynh T, Ramachandran G, Banerjee S, Monteiro J, Stenzel M, Sandler DP *et al.* Comparison of methods for analyzing left-censored occupational exposure data. *Ann Occup Hyg* 2014; **58**: 1126–1142.
40 Radiation Protection Standard. *Maximum Exposure Levels to Radiofrequency Fields — 3 kHz to 300 GHz, Radiation Protection Series Publication No. 3*. Australian Radiation Protection and Nuclear Safety Agency: Australia, 2002, pp 1–128.
41 Urbinello D, Joseph W, Verloock L, Martens L, Röösli M. Temporal trends of radio-frequency electromagnetic field (RF-EMF) exposure in everyday environments across European cities. *Environ Res* 2014; **134**: 134–142.
42 Bhatt CR, Thielens A, Redmayne M, Abramson MJ, Billah B, Sim MR *et al.* Measuring personal exposure from 900 MHz mobile phone base stations in Australia and Belgium using a novel personal distributed exposimeter. *Environ Int* 2016; **92–93**: 388–397.
43 Thielens A, Agneessens S, Verloock L, Tanghe E, Rogier H, Martens L *et al.* On-body calibration and processing for a combination of two radio-frequency personal exposimeters. *Radiat Prot Dosimetry* 2015; **163**: 58–69.
44 Bergqvist U, Friedrich G, Hamnerius Y *et al.* Mobile telecommunication base stations–exposure to electromagnetic fields. Report of a short term mission within COST-244bis. Available at: ftp://ftp.cordis.lu/pub/ist/docs/ka4/cost_244_base_station_emf.pdf (last accessed 12 January 2016).
45 Schmid G, Preiner P, Lager D, Uberbacher R, Georg R. Exposure of the general public due to wireless LAN applications in public places. *Radiat Prot Dosimetry* 2007; **124**: 48–52.
46 Röösli M, Frei P, Bolte J, Neubauer G, Cardis E, Feychting M *et al.* Conduct of a personal radiofrequency electromagnetic field measurement study: proposed study protocol. *Environ Health* 2010; **9**: 23.
47 Röösli M, Frei P, Mohler E, Braun-Fahrlander C, Burgi A, Frohlich J *et al.* Statistical analysis of personal radiofrequency electromagnetic field measurements with nondetects. *Bioelectromagnetics* 2008; **29**: 471–478.
48 Henderson S, Tjong L, Wijayasinghe D. Survey of radiofrequency radiation levels across Melbourne. In: *The 39th Australasian Radiation Protection Society Conference*, Hobart, Tasmania, Australia, 2014.

Chapter 6: Use of mobile and cordless phones and change in cognitive function

Overview

In previous chapters, far-field RF-EMF exposure assessments in human environments were discussed. Therefore, the work mainly addressed the WHO's high priority research agenda particularly related to RF-EMF dosimetry (50). This chapter, on the other hand, discusses the research performed to address the WHO's another high priority RF-EMF research agenda related to epidemiology - performance of prospective cohort studies of children with outcomes including behavioural and neurological disorders (50). In this chapter, I assessed psychological health outcomes, particularly cognitive development of young children in relation to their use of mobile and cordless phones (i.e. near-field exposure). The cross-sectional findings on the associations between the use of mobile phones (MPs) and cordless phones (CPs) in primary school children and effects on their cognitive function were published in 2016 (18). This chapter examines possible longitudinal associations between the use of MPs and CPs in a cohort of primary school children and effects on their cognitive function over a one year period.

The findings showed that children's ownership or use of a MP was low (compared to use of a CP), but increased from baseline to follow-up. The use of a CP at home remained fairly equal at baseline and follow-up. The 'increase' in MP usage was associated with: i) larger reduction in response time for the Go/NoGo task, ii) smaller reduction in the number of total errors for spatial problem solving task, and iii) larger increase in response time for a Stroop interference task. The increase in CP usage had no significant effect on most of the changes in cognitive outcomes. However, the 'increase' in number of CP calls weekly group had smaller increase in accuracy in the detection task compared to those in the ‘no change or decrease’ group. The overall findings suggest that there was limited evidence that change in the use of MPs/CPs in primary school children was associated with change in cognitive function.

Declaration for Thesis Chapter 6

Manuscript: **Bhatt CR,** Benke G, Smith CL, Redmayne M, Dimitriadis C, Dalecki A, Macleod S, Sim MR, Croft RJ, Wolfe R, Kaufman J, Abramson MJ. Use of mobile and cordless phones and change in cognitive function: A prospective cohort analysis of Australian primary school children [Accepted in Environmental Health (DOI : 10.1186/ s12940-017-0250-4)]

Declaration by candidate

In the case of Chapter 7, the nature and extent of my contribution to the work was the following:

Nature of contribution	**Extent of contribution (%)**
Data analysis, manuscript preparation and editing, and submission the manuscript	75%

The following co-authors contributed to the work. Where co-authors are students at Monash University, the extent of their contribution in percentage terms is stated:

Names	**Nature of contribution**
Geza Benke	Study concept and design, study funding, data collection, data analysis and interpretation, manuscript editing, revision of submitted manuscript, and supervision
Catherine L. Smith	Data analysis and interpretation, manuscript editing, and revision of submitted manuscript
Mary	Data interpretation, manuscript editing, and revision of submitted

Redmayne	manuscript and supervision
Christina Dimitriadis	Coordinated and supervised data collection, manuscript editing, and revision of submitted manuscript
Anna Dalecki	Coordinated data collection, manuscript editing, and revision of submitted manuscript
Skye Macleod	Study design, questionnaire development, ethics approval, and data collection, manuscript editing, and revision of submitted manuscript
Malcolm R. Sim	Study concept and design, study funding, data interpretation, manuscript editing, and revision of submitted manuscript
Rodney J. Croft	Study design, data collection and interpretation, manuscript editing, and revision of submitted manuscript
Rory Wolfe	Study design, data analysis and interpretation, manuscript editing, and revision of submitted manuscript
Jordy Kaufman	Study design, data analysis and interpretation, manuscript editing, and revision of submitted manuscript
Michael J. Abramson	Study concept and design, study funding, data interpretation, manuscript editing, revision of submitted manuscript, and supervision

The undersigned hereby certify that the above declaration correctly reflects the nature and extent of the candidate's and co-authors' contribution to this work.

Candidate's Signature	[redacted]	Date 28/04/2017

Main Supervisor's Signature	[redacted]	Date 28/04/2017

Use of mobile and cordless phones and change in cognitive function: a prospective cohort analysis of Australian primary school children

ABSTRACT

Background: Some previous studies have suggested an association between children's use of mobile phones (MPs)/cordless phones (CPs) and development of cognitive function. We evaluated possible longitudinal associations between the use of MPs and CPs in a cohort of primary school children and effects on their cognitive function.

Methods: Data on children's socio-demographics, use of MPs and CPs, and cognitive function were collected at baseline (2010–2012) and follow-up (2012–2013). Cognitive outcomes were evaluated with the CogHealth™ test battery and Stroop Color-Word test. The change in the number of MP/CP voice calls weekly from baseline to follow-up was dichotomized: "an increase in calls" or a "decrease/no change in calls". Multiple linear regression analyses, adjusting for confounders and clustering by school, were performed to evaluate the associations between the change in cognitive outcomes and change in MP and CP exposures.

Results: A larger proportion of children used a CP (76% at baseline and follow-up), compared to a MP (31% at baseline and 43% at follow-up). Of 26 comparisons of changes in cognitive outcomes, four demonstrated significant associations. The increase in MP usage was associated with faster response time for response inhibition, lower accuracy for spatial problem solving and slower response time for the Stroop interference task. Except for reduced detection task accuracy, the increase in CP usage had no effect on the changes in cognitive outcomes.

Conclusion We found limited evidence that change in the use of MPs or CPs in primary school children was associated with change in cognitive function.

Background

The use of mobile phones (MPs) and cordless phones (CPs) by young children has become common worldwide [1-6]. This has raised concerns regarding the potential health and psychological effects of MPs and CPs on the developing brains of children [7-11]. The World Health Organization has identified research into children's behavioral and neurological outcomes associated with radio-frequency electromagnetic field (RF-EMF) exposure as a high priority RF-EMF agenda [8].

The use of MPs or/and CPs in children has been associated with negative consequences in cognitive functioning [1, 12], including memory performance [11] and emotional and behavior difficulties [13]. However, there are few community-based epidemiological studies involving children that assessed effects of MP and/or CP use on cognitive functioning [1, 10-12, 14]. The findings of these studies are inconclusive [1, 11, 12, 14]. A recent Swiss study involving adolescents found a negative association between MP and CP use with figural memory [11]. The Amsterdam Born Children and their Development (ABCD) study showed inconsistent associations between MP and CP use and cognitive function [14]. Furthermore, our cross-sectional analysis of the ExPOSURE (Examination of Psychological Outcomes in Students Using Radiofrequency dEvices) study found little evidence for an association between the use of MPs and CPs and cognitive effects in a cohort of primary school children in Australia [10].

The aim of this prospective analysis of the ExPOSURE study data was to evaluate possible longitudinal associations between the use of MPs and CPs in a cohort of primary school children and effects on their cognitive function.

Methods

Study design and participants

A longitudinal study was undertaken among primary school children (the 4^{th} year) in Melbourne and Wollongong, Australia. Baseline (n=619) and follow-up (n=412) data were collected from 36 schools during November 2010 – February 2012 and March 2012 – March 2013, respectively.

Written or verbal informed consent was obtained from the parent/guardian of each student, teachers of the participating classes, and principals of the participating schools. The study also received approvals from the Victorian Department of Education and Early Childhood Development, New South Wales Department of Education and Communities, Catholic Education Offices of Victoria and New South Wales, Monash University Human Research Ethics Committee and the University of Wollongong Human Research Ethics Committee.

The information on socio-demographics and that related to MP or/and CP use or ownership were collected at baseline and follow-up. Cognitive outcomes were also assessed at the two time points.

Exposure assessment

The parents/guardians of participating children completed a modified and validated questionnaire from the Interphone study [15], which collected information on their children's MP and CP use, such as average number of MP calls (made and received) weekly, duration of each (outgoing and incoming) MP call, average number of text messages or SMS (sent and received) weekly, average number of CP calls (made and received) weekly, and duration of each call on CP weekly. In addition, we also gathered socio-demographic information such as age, sex, country of birth, ethnicity (languages other than English spoken at home) and residential post code. The parents were also asked about their perception of their and their family's health risk in relation to MP use. The children, assisted by research staff, completed a questionnaire about whether or not they owned or used a MP, laterality of MP use, handedness (right or left handed), and the amount of gaming and computer/Internet use.

Outcome assessment

Cognitive outcomes were assessed with a computerized CogHealth™ test battery (CogState, Melbourne, AU, 2005)[1, 10, 12], and the Stroop Color-Word test [16].

CogHealth™ evaluated signal detection (simple reaction), identification (choice reaction), one-back (working memory), one card learning (visual attention), Go/No-Go (response inhibition), and Groton maze learning (spatial and executive ability) [10]. Further details of testing administration are discussed elsewhere [10, 12]. The total number of errors for the spatial problem solving function, and response times (ms) and accuracy (%) for the rest of the CogHealth™ cognitive tests were assessed.

The Stroop Color-Word test: This test assessed the ability to name colors and words that are presented in conjunction with interfering stimulus characteristics (e.g. naming the written word 'red', presented in blue hue) [17]. The task has four sub-tests, two to provide baseline information (no interference), and two interference conditions [1, 12]. These tests measured response time for each form and time ratios were subsequently estimated. Further details of the test can be found in the literature [1, 16].

Statistical analyses

Descriptive analyses were performed for socio-demographics and MP and CP use. The descriptive analyses for exposure measures, CogHealth™ tasks, Stroop Color-Word test, and regression analyses were performed for the students taking part both in baseline and follow-up (n=412). Socio-economic status (SES) was estimated from socio-economic indexes for areas in accordance with children's residential postal codes [18].

RF-EMF exposure measures were the total number of voice calls (made and received) weekly for MP and CP separately. We used reported numbers of MP and CP calls as the proxies for MP and CP exposures, respectively [1, 10, 12], because they may be more accurate in ascertaining the phone use compared to the 'duration of calls' [19, 20]. We did not consider SMS use as an exposure, firstly because RF-EMF exposure to the head due to SMS would be very low, and secondly because SMS use was very low in this age group. MP use was low in both surveys. For the MP/CP users, the numbers of reported voice calls weekly on MPs and CPs were low (i.e. median at baseline = 2), with no use of MP/CP represented as zero calls. Therefore, the exposure metrics at baseline and follow-up were further classified in terms of the three groups: no use ('none'), $\leq$ 2 voice calls weekly on MP/CP ('some'), and > 2 voice calls weekly on MP/CP ('more'). Cognitive parameters were summarized across these three groups. The mean response time of each test was $\log_{10}$ transformed and the square root of each accuracy score was arcsine transformed [1, 12]. The Stroop Color-Word test data were analyzed by comparing the time ratios of response times (in seconds) of form B and form A [i.e. (B-A)/A], and those of form D and form C [i.e. (D-C)/C].

Multiple linear regression models with robust standard errors, allowing for clustering of students within schools, were used to assess the association between the change in cognitive outcome (follow-up minus baseline) in children who increased their MP (or CP) weekly calls from baseline to follow-up, and those who did not increase their MP (or CP) usage. The models were adjusted for age at baseline, sex, ethnicity, SES (classified into quintiles), lag time between baseline and follow-up, handedness and total screen time weekly (i.e. gaming and computer/Internet use).

Changes in MP and CP voice calls weekly from baseline to follow up were dichotomized as follows: 0 = decrease or no change in number of MP and CP voice calls weekly, or 1 = increase in number of MP and CP voice calls weekly. The models also considered the potential interaction between gender and MP and CP use in an exploratory analysis. Seven children with attention deficit hyperactivity disorder were excluded from the regression analysis. For all analyses, $p \leq 0.05$ (two-sided) was considered as statistically significant. Data analysis was performed with STATA ver13.1 (StataCorp, College Station, TX, USA) or SPSS (version 22, IBM Corp, Armonk, NY, USA).

Results

Descriptive data

Table 1 shows socio-demographic characteristics, and MP and CP use of the children taking part in baseline and follow-up. Of 619 baseline participants, 412 (66.5%) took part in the follow-up study. The mean (± SD) time lag between the baseline and follow-up studies was 12.4 ± 2 months. Most of the participants at baseline and follow-up were from high socio-economic areas. Ethnicity (language other than English spoken at home) and country of birth (Australia) of children was similar at baseline and follow-up. The handedness also remained largely unchanged from baseline and follow-up – right (87%), left (10.3%), no preference (2.2%) [baseline], and right (86%), left (10%) and no preference (~ 4%) [follow-up].

According to the parental responses, nearly 31% of children at baseline and 43% at follow-up owned or used a MP. In contrast, 57% of children at baseline and 68% at follow-up reported having owned or used a MP. The use of a CP at home was reported for 76% of the children both at baseline and follow-up.

Table 2 shows MP and CP calls, MP SMS, and MP and CP use for the children who took part both in baseline and follow-up. Overall, weekly MP voice calls and SMS significantly increased ($p<0.001$ for both), whereas weekly CP voice calls remained unchanged ($p=0.26$), from baseline to follow-up. For the MP/CP users, the median numbers of voice calls (made and received) weekly for MP and CP were 2 and 2 at baseline, and 2.5 and 2 at follow-up, respectively.

Of the parents taking part in both waves of surveys, 33.6% at baseline and 31% at follow-up considered that MPs posed low risk to them and their family's health. Likewise, 21% at baseline and 22% at follow-up considered that MPs posed moderate risk. However 37% at baseline and follow-up did not know if MP use posed a health risk. Only a few parents (nearly 5% at baseline and follow-up) considered MPs to represent a high health risk. Five percent at baseline and follow-up also considered MP use to pose no health risk.

Table 1 Socio-demographic, mobile and cordless phone use characteristics of children

Variables	Baseline [n=619]	Follow-up [n=412]
Age (mean ± SD)	10 ± 0.4 years	11 ± 0.5 years
Sex	53% (n=329) girls	55% (n=227) girls
Ownership/use of a MP (parent's response)	31.0% (n=187)	43.3% (n=168)
Ownership/and use of a MP (children's response)	57.3% (n=353)	67.9% (n=279)
Laterality of MP use	Right: 68.2% (n=262) Left: 11.5% (n=44) Both: 18.5% (n=71)	Right: 74.2% (n=250) Left: 10.7% (n=36) Both: 14.0% (n=47)
Use of a CP at home	76% (n=470)	76.2% (n=314)
Average duration per call (minutes) weekly	Median (25^{th}, 75^{th} percentiles)	Median (25^{th}, 75^{th} percentiles)
A call dialed on MP	2 (1, 3)	2 (1, 3)
A call received on MP	1.5 (0, 3)	1.5 (0.5, 3)
Call (dialed & received) on CP	3.5 (2, 5)	4 (2, 5.5)

Table 2 MP and CP exposure measures [baseline & follow-up participants (n=412)]

Total number of MP and CP calls/SMS weekly[a]	Baseline	Follow-up	
	Median (25th, 75th percentiles)		[b]p-value
MP voice calls (dialed & received)	2 (1,5)	2.5 (1,5.2)	<0.001
MP SMS (sent & received)	0.5 (0,4)	2 (0,7.5)	<0.001
CP voice calls (dialed & received)	2 (1,4)	2 (1,4)	0.26
MP and CP usage[c]	Proportion (number) of children		
MP voice calls			
No use	69.7 % (n=279)	57.6% (n=220)	**<0.001[d]**
Some use (≤ 2 calls weekly)	15.3% (n=61)	22.0% (n=84)	
More use (> 2 calls weekly)	15.0% (n=60)	20.4% (n=78)	
CP voice calls			
No use	17% (n=67)	20% (n=76)	**0.04 [d]**
Some use (≤ 2 calls weekly)	47.5% (n=186)	46% (n=177)	
More use (> 2 calls weekly)	35.5% (n=139)	34% (n=129)	

[a]Data included MP & CP users only, [b]Wilcoxon signed-rank test, [c]Data included both non-users and users, [d] Fleiss-Everitt Chi square test based on non-missing data

There were no significant differences between those who continued to participate (n=412) and drop outs (n=207) in age, sex, ethnicity, ownership or use of MP, laterality of MP use, handedness, total average number of calls (made and received) weekly on MPs, total average number of calls (made and received) weekly on CPs, total average number of SMS messages (sent and received) weekly on MPs. Nor were there differences in their baseline response times for the detection task, visual recognition and attention, and working memory; response time and accuracy for the identification task, or response inhibition task.

Compared to the children who were followed-up, the drop-outs were more likely to be in the lower two quintiles of SES, rather than the higher three quintiles of SES. The drop-outs also owned and used MPs and CPs less, had higher Stroop time ratios, response inhibition task, less accuracy in the Groton maze and detection tasks, visual recognition and attention and working memory (data not shown).

Tables 3, 4 and 5 summarize cognitive outcome data of the children who used MP and CP and took part in both waves of surveys. Table 3 compares data of CogHealth™ cognitive outcomes (untransformed) in those children who used MPs. Table 4 compares the data of the cognitive outcomes in those children who used CPs. Table 5 summarizes the cognitive outcome data of the Stroop Color-Word tests. The response times tended to be faster and accuracy similar or better at follow-up compared to baseline in the most of cases.

Association between change in cognitive function, and change in the use of mobile and cordless phones

Table 6 compares the change in cognitive outcome (follow-up minus baseline) between those who increased their MP/CP weekly calls from baseline to follow-up, and those who did not increase their MP/CP usage.

Compared to the ‘no change or decrease’ group, the ‘increase’ in total average number of MP calls weekly group had significantly: i) lower mean response time for the Go/NoGo task, ii) higher mean number of total errors in executing the Groton maze learning task, and iii) higher mean response time for the Stroop time ratio ((B-A)/A).

The change in CP usage had no significant effect on most of the changes in cognitive outcomes. However, the ‘increase’ in number of CP calls weekly group had lower mean accuracy in the detection task compared to those in the ‘no change or decrease’ group.

We did not find gender to be an effect modifier (results not shown).

Table 3 Descriptive statistics for mobile phone voice call use and CogHealth™ tasks [median (25th, 75th percentiles)][a]

Tests	Parameters	Baseline		Follow-up	
		Groups (n)	Median (25th, 75th percentiles)	Groups (n)	Median (25th, 75th percentiles)
Simple reaction time (Detection task)	Response time (ms)	None (276)	344 (302, 413)	None (243)	317 (288, 359)
		Some (59)	350 (297, 410)	Some (57)	315 (284, 342)
		More (57)	380 (321, 417)	More (83)	316 (282, 362)
	Accuracy (%)	None (278)	97 (92, 100)	None (243)	97 (95, 100)
		Some (61)	97 (92, 100)	Some (57)	97 (95, 100)
		More (58)	96 (83, 96)	More (83)	97 (93, 100)
Choice reaction time (Identification task)	Response time (ms)	None (277)	588 (524, 686)	None (243)	549 (481, 619)
		Some (61)	579 (518, 655)	Some (57)	525 (484, 577)
		More (58)	607 (550, 699)	More (83)	558 (493, 601)
	Accuracy (%)	None (278)	94 (86, 97)	None (243)	94 (88, 97)
		Some (61)	94 (88, 97)	Some (57)	94 (88, 97)
		More (58)	94 (86, 97)	More (83)	94 (89, 97)
One-back task (Working memory)	Response time (ms)	None (278)	965 (792, 1113)	None (243)	863 (707, 1035)
		Some (61)	1023 (793, 1164)	Some (57)	860 (741, 971)
		More (57)	976 (826, 1158)	More (83)	930 (748, 998)
	Accuracy (%)	None (278)	88 (77, 94)	None (243)	94 (86, 97)
		Some (61)	94 (81, 97)	Some (57)	92 (86, 97)
		More (58)	86 (69, 94)	More (83)	94 (82, 97)

One card learning task (Visual recognition memory & attention)	Response time (ms)	None (278)	1072 (885, 1322)	None (243)	1047 (854, 1273)
		Some (61)	1130 (881, 1387)	Some (57)	1004 (875, 1170)
		More (58)	1143 (887, 1293)	More (83)	1052 (936, 1225)
	Accuracy (%)	None (278)	59 (49, 66)	None (243)	64 (54, 71)
		Some (61)	57 (50, 64)	Some (57)	63 (53, 68)
		More (58)	58 (49, 64)	More (83)	64 (56, 70)
Go/NoGo (Response inhibition task)	Response time (ms)	None (276)	628 (539, 710)	None (243)	592 (505, 676)
		Some (60)	600 (557, 707)	Some (57)	549 (484, 628)
		More (58)	669 (599, 740)	More (83)	574 (516, 655)
	Accuracy (%)	None (277)	98 (94, 100)	None (243)	98 (96, 100)
		Some (61)	98 (94, 98)	Some (57)	98 (94, 98)
		More (58)	96 (91, 98)	More (83)	98 (96, 100)
Groton maze learning task (Spatial & executive ability)	Total number of errors	None (278)	69 (54, 86)	None (243)	55 (46, 67)
		Some (61)	65 (56, 76)	Some (57)	56 (49, 69)
		More (58)	72 (55, 89)	More (83)	59 (49, 72)

[a] Statistics of children who took part in baseline and follow-up (n=412)

Table 4 Descriptive **s**tatistics for cordless phone voice call use and CogHealth™ tasks [median (25th, 75th percentiles)][a]

Tests	Parameters	Baseline		Follow-up	
		Groups (n)	Median (25th, 75th percentiles)	Groups (n)	Median (25th, 75th percentiles)
Simple reaction time (Detection task)	Response time (ms)	None (66) Some (183) More (135)	336 (306, 394) 347 (299, 404) 350 (307, 414)	None (76) Some (177) More (123)	326 (294, 373) 325 (288, 357) 309 (279, 352)
	Accuracy (%)	None (67) Some (185) More (137)	95 (89, 100) 97 (94, 100) 95 (87, 100	None (76) Some (177) More (123)	97 (95, 100) 97 (95, 100) 97 (93, 100
Choice reaction time (Identification task)	Response time (ms)	None (67) Some (185) More (137)	573 (526, 662) 589 (521, 665) 596 (536, 685)	None (76) Some (177) More (123)	545 (496, 595) 559 (489, 611) 529 (476, 592)
	Accuracy (%)	None (67) Some (185) More (137)	91 (85, 97) 94 (86, 97) 94 (86, 97)	None (76) Some (177) More (123)	94 (91, 97) 94 (88, 97) 94 (88, 97)
One-back task (Working memory)	Response time (ms)	None (67) Some (185) More (137)	958 (751, 1062) 939 (793, 1114) 992 (818, 1132)	None (76) Some (177) More (123)	883 (729, 985) 865 (715, 1022) 865 (712, 1020)
	Accuracy (%)	None (67) Some (185) More (137)	89 (74, 94) 89 (77, 94) 89 (74, 94)	None (76) Some (177) More (123)	93 (86, 97) 94 (86, 97) 91 (84, 97)

One card learning task (Visual recognition memory & attention)	Response time (ms)	None (67)	1015 (827, 1274)	None (76)	1065 (940, 1345)
		Some (185)	1071 (887, 1312)	Some (177)	1042 (875, 1218)
		More (137)	1150 (874, 1340)	More (123)	1013 (862, 1224)
	Accuracy (%)	None (67)	56 (49, 65)	None (76)	64 (56, 70)
		Some (185)	60 (51, 66)	Some (177)	65 (56, 72)
		More (137)	59 (50, 65)	More (123)	61 (53, 69)
Go/NoGo (Response inhibition task)	Response time (ms)	None (66)	616 (558, 694)	None (76)	569 (517, 656)
		Some (185)	633 (541, 720)	Some (177)	580 (503, 662)
		More (136)	631 (565, 706)	More (123)	583 (503, 689)
	Accuracy (%)	None (67)	98 (94, 98)	None (76)	98 (96, 100)
		Some (185)	98 (94, 100)	Some (177)	98 (96, 100)
		More (136)	96 (94, 100)	More (123)	98 (94, 100)
Groton maze learning task (Spatial & executive ability)	Total number of errors	None (67)	65 (55, 84)	None (76)	56 (46, 67)
		Some (185)	69 (54, 80)	Some (177)	56 (46, 68)
		More (137)	68 (55, 84)	More (123)	58 (48, 70)

[a] Statistics of children who took part in baseline and follow-up (n=412)

Table 5 Descriptive **s**tatistics [median (25th, 75th percentiles)] for the Stroop Color-Word test time ratios *vs* phone use type [CP (cordless phone) or MP (mobile phone)][a]

Forms	Parameters	Exposure type	Baseline	Exposure type	Follow-up
		Groups (n)	Median (25th, 75th percentiles)	Groups (n)	Median (25th, 75th percentiles)
Stroop ratio ((B-A)/A)	Time ratio	MP voice calls		MP voice calls	
		None (276)	0.09 (0.02, 0.16)	None (218)	0.11 (0.03, 0.22)
		Some (60)	0.10 (0.02, 0.18)	Some (84)	0.13 (0.06, 0.22)
		More (60)	0.08 (0.003, 0.15)	More (78)	0.10 (0.05, 0.20)
		CP voice calls		CP voice calls	
		None (66)	0.07 (0.01, 0.14)	None (76)	0.11 (0.04, 0.20)
		Some (184)	0.89 (0.007, 0.17)	Some (177)	0.12 (0.04, 0.24)
		More (138)	0.11 (0.04, 0.17)	More (127)	0.10 (0.04, 0.20)
Stroop ratio ((D-C)/C)	Time ratio	MP voice calls		MP voice calls	
		None (276)	0.69 (0.53, 0.91)	None (218)	0.66 (0.52, 0.84)
		Some (60)	0.65 (0.52, 0.81)	Some (84)	0.60 (0.45, 0.81)
		More (60)	0.68 (0.59, 0.87)	More (78)	0.66 (0.50, 0.83)
		CP voice calls		CP voice calls	
		None (66)	0.60 (0.52, 0.77)	None (76)	0.56 (0.46, 0.71)
		Some (184)	0.70 (0.53, 0.93)	Some (177)	0.67 (0.53, 0.86)
		More (138)	0.68 (0.57, 0.89)	More (127)	0.66 (0.52, 0.85)

[a] Statistics of children who took part in baseline and follow-up (n=412)

Table 6 Regression results comparing the change in cognitive outcome (follow-up minus baseline) between those who increased their MP (or CP) calls weekly from baseline to follow-up, and those who did not increase their MP (or CP) usage

		Difference in cognitive outcome means between those who increased MP (or CP) use and those did not increase or reduced their use			
		Voice calls on MP		Voice calls on CP	
Tests	Parameters	Estimate	95% CI	Estimate	95% CI
Detection task	Response time (ms)[a]	-0.008	-0.042, 0.027	0.007	-0.019, 0.033
	Accuracy (%)[b]	0.024	-0.036, 0.084	**-0.069**	**-0.127, -0.012**
Identification task	Response time (ms)[a]	-0.008	-0.034, 0.018	0.007	-0.011, 0.024
	Accuracy (%)[b]	0.012	-0.044, 0.067	-0.047	-0.097, 0.002
One-back memory task (Working memory)	Response time (ms)[a]	0.009	-0.018, 0.036	0.017	-0.006, 0.041
	Accuracy (%)[b]	0.014	-0.048, 0.076	-0.029	-0.077, 0.019
One card learning task (Visual recognition memory & attention)	Response time (ms)[a]	0.005	-0.033, 0.043	-0.0008	-0.034, 0.032
	Accuracy (%)[b]	-0.022	-0.054, 0.009	-0.011	-0.049, 0.026
Go/NoGo (Response inhibition task)	Response time (ms)[a]	**-0.030**	**-0.054, -0.006**	0.009	-0.013, 0.032
	Accuracy (%)[b]	0.011	-0.037, 0.059	-0.013	-0.060, 0.034

Groton maze learning task	Accuracy (total no. of errors)	**6.22**	**2.13, 10.31**	-2.77	-8.77, 3.24
Time ratio ((B-A)/A)	Response time (s)	**0.056**	**0.021, 0.090**	-0.028	-0.069, 0.013
Time ratio ((D-C)/C)	Response time (s)	-0.048	-0.127, 0.033	-0.003	-0.066, 0.059

Reference group: no change or decrease in total average number of MP or CP calls weekly (exposure dichotomized: “no change or decrease” and “increase” in total average number of MP and CP voice calls weekly).
[a] $\log_{10}$ transformed data, [b] Arcsine transformed hit rate
Adjusted for age at baseline, sex, ethnicity, SES (classified into quintiles), lag time between baseline and follow-up, handedness, and total screen time weekly (gaming and computer/Internet use).
The **bold numbers** represent significant assoctions

Discussion

This community-based longitudinal cohort study investigated whether the change in MPs/CPs in primary school children was associated with changes in cognitive function. We found that number of calls and SMS weekly on MPs increased, whereas CP calls weekly remained unchanged from baseline to follow-up. Our results provide only limited evidence that change in the use of MPs/CPs in primary school children was associated with change in cognitive function.

The usage/ownership of MPs found in this sample of Australian children was low, but comparable to rates reported elsewhere. In the US, the use of MPs in children (aged 8 and under) increased from 38% to 72% during 2011-2013 [21], In Europe, 33–83% of children aged up to 14 years [2, 4, 22], and 48% of Dutch children aged 5-6 years either used or owned a MP [14].

A relatively larger proportion of children used a CP, compared to a MP, which is similar to that found in the Netherlands [14]. The number MP and CP calls reported in our study is also comparable to that observed elsewhere [3, 14]. We found that a lower percentage of primary school children own/use a MP compared to ownership/usage rates reported in secondary school children [1, 11].

The follow-up analysis also showed that more children reported using/owning a MP than was reported by parents. A similar pattern was seen in our cross-sectional data [10]. This could be due to how the questions related to MP ownership and/or uses were asked and/or how they were understood by the parents and children. The potential implications of this for epidemiological studies have been discussed in the literature [1, 10, 23]. We suggest that the findings associated with the use of CP could be more accurate since the CP was used only at home and parents may thus have directly observed their child's CP exposures.

The children had better cognitive performance at follow-up compared to baseline, which is expected as a natural part of development and has been reported in literature [24]. In the cross-sectional analysis [10], the 'more' MP users had slower responses for Go/NoGo task. However, this longitudinal analysis found that the 'increase' in MP calls group had faster response time for the task. Furthermore, the cross-sectional findings observed that the 'more' CP (but not MP) users took longer when trying to overcome distraction (Stroop). But, the longitudinal analysis showed that only the 'increase' in MP calls group had higher mean response time for the Stroop interference task ((B-A)/A).

The cross-sectional analysis also showed the 'more' users of MPs had lower accuracy for visual recognition memory and attention, and identification tasks [10]. We did not see any significant findings in relation to these tasks in our longitudinal data analysis. The 'increase' in MP calls group had lower accuracy in executing the Groton maze learning task, similar pattern was not seen in the findings of the cross-sectional analysis. The 'increase' in the CP calls group had lower accuracy in the detection task compared to those in the 'no change or decrease' group. Similar results for the 'more' users of CP was not seen in the cross-sectional analysis. These inconsistences between our cross-sectional and follow-up findings suggest that these may represent chance findings.

Our previous longitudinal study involving Australian secondary school children showed an increase in MP voice calls was associated with slower simple response time, but quicker working memory [1]. We did not find any similar results in the current study. A Swiss cohort study found that brain RF-EMF exposure among a ‘high’ exposed group (aged 12-17 years) was associated with a decrease in figural memory [11]. The memory tasks (i.e. one–back and one card learning) used in our study and the figural memory task were different. Therefore, caution is advised when comparing the findings. In the Netherlands, children aged 5-6 years in the Netherlands showed that high CP users demonstrated slower response times in an inhibitory control and cognitive flexibility compared to non-users [14]. Although not identical, to the extent that the inhibitory control test and Go/NoGo task in our paper reflect the ‘inhibitory control’ cognitive process, and if CP/MP affects it, we would expect to see a similar pattern of results across the two studies. However, this was not the case: the Netherlands study reported slower reaction time in ‘high’ CP users, while we observed a faster reaction time amongst the group that increased their MP use.

Our study is the first to evaluate a longitudinal association of MP/CP use and change in cognition in a representative community-based sample of young children. We prospectively collected data at two time points. The study cohort consisted of a relatively large sample size, compared to those employed in provocation studies [25-27]. We assessed eight cognitive tasks, compared to the Swiss study (which only assessed two tasks) and the ABCD study (which assessed four tasks). This allowed us to look for potential effects on different cognitive domains as well as for whether consistent patterns of effects were present across multiple tasks (vs just in one task) within a cognitive domain.

The main limitation of the study was that phone exposure measures were self-reported. Our study was therefore likely to misclassify exposure and could provide biased findings. Objective exposure measurements using MP-based apps should be considered for prospective epidemiological studies, whenever possible [28]. Furthermore, the one-year follow-up time in our study may not be long enough to detect potential changes in cognitive outcomes associated with MPs/CPs exposure. A further follow-up may be more sensitive at determining whether a long-term usage of MPs and CPs affects cognition [29].

Conclusions

Our study shows that a larger proportion of children used CPs compared to MPs. The increase in MP usage was significantly associated with slower response time for response inhibition task, spatial problem solving and a Stroop interference task. The increase in CP usage had no significant effect on the most of the changes in cognitive outcomes. Due to the small numbers of mobile and cordless phone calls, the observed changes in cognitive tasks could be pure chance findings. The use of mobile phones, as reported by children and parents was different. This should be taken into account in future studies by performing objective measurements of mobile phone exposures, whenever possible.

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Conflict of Interest

MJA and CD hold small parcels of shares in Telstra which operates a cell telephone network in Australia. MR received salary from the NHMRC grant during the first part of the work on this paper. The other authors declare no conflict of interest.

REFERENCES

1. Thomas S, Benke G, Dimitriadis C, Inyang I, Sim M, Wolfe R, Croft RJ, Abramson MJ. Use of mobile phones and changes in cognitive function in adolescents. Occup Environ Med. 2010; 67(12):861-6.
2. Mezei G, Benyi M, Muller A. Mobile phone ownership and use among school children in three Hungarian cities. Bioelectromagnetics 2007; 28(4):309-15.
3. Redmayne M. New Zealand adolescents' cellphone and cordless phone user-habits: are they at increased risk of brain tumours already? A cross-sectional study. Environ Health 2013, 12:5.
4. Böhler E, Schüz J. Cellular telephone use among primary school children in Germany. Eur J Epidemiol. 2004; 19(11):1043-50.
5. Söderqvist F, Hardell L, Carlberg M, Mild KH. Ownership and use of wireless telephones: a population-based study of Swedish children aged 7–14 years. BMC Public Health 2007; 7(1):105.
6. Kabali HK, Irigoyen MM, Nunez-Davis R, Budacki JG, Mohanty SH, Leister KP, Bonner RL, Jr. Exposure and Use of Mobile Media Devices by Young Children. Pediatrics 2015; 136(6):1044-50.
7. Kheifets L, Repacholi M, Saunders R, Van Deventer E. The sensitivity of children to electromagnetic fields. Pediatrics 2005; 116(2):e303-e313.

8. van Deventer E, van Rongen E, Saunders R: WHO research agenda for radiofrequency fields. Bioelectromagnetics 2011; 32(5):417-21.

9. Bailin A, Milanaik R, Adesman A. Health implications of new age technologies for adolescents: a review of the research. Curr Opin Pediatr. 2014; 26(5):605-19.

10. Redmayne M, Smith CL, Benke G, Croft RJ, Dalecki A, Dimitriadis C, Kaufman J, Macleod S, Sim MR, Wolfe R, Abramson MJ. Use of mobile and cordless phones and cognition in Australian primary school children: a prospective cohort study. Environ Health 2016; 15(1):26.

11. Schoeni A, Roser K, Röösli. Memory performance, wireless communication and exposure to radiofrequency electromagnetic fields: A prospective cohort study in adolescents. Environ Int. 2015; 85:343-51.

12. Abramson MJ, Benke GP, Dimitriadis C, Inyang IO, Sim MR, Wolfe RS, Croft RJ. Mobile telephone use is associated with changes in cognitive function in young adolescents. Bioelectromagnetics 2009; 30(8):678-86.

13. Sudan M, Olsen J, Arah OA, Obel C, Kheifets L. Prospective cohort analysis of cellphone use and emotional and behavioural difficulties in children. J Epidemiol Community Health 2016:jech-2016-207419.

14. Guxens M, Vermeulen R, van Eijsden M, Beekhuizen J, Vrijkotte TG, van Strien RT, Kromhout H, Huss A. Outdoor and indoor sources of residential radiofrequency electromagnetic fields, personal cell phone and cordless phone use, and cognitive function in 5-6 years old children. Environ Res. 2016; 150:364-74.

15. Cardis E, Richardson L, Deltour I, Armstrong B, Feychting M, Johansen C, Kilkenny M, McKinney P, Modan B, Sadetzki S. The INTERPHONE study: design, epidemiological methods, and description of the study population. Eur J Epidemiol. 2007; 22(9):647-64.

16. Stroop JR. Studies of interference in serial verbal reactions. J Exp Psychology 1935; 18(6):643.

17. Van der Elst W, Van Boxtel MP, Van Breukelen GJ, Jolles J. The Stroop Color-Word Test influence of age, sex, and education; and normative data for a large sample across the adult age range. Assessment 2006; 13(1):62-79.

18. Thomée S, Härenstam A, Hagberg M. Mobile phone use and stress, sleep disturbances, and symptoms of depression among young adults-a prospective cohort study. BMC Public Health 2011; 11(1):66.

19. Samkange-Zeeb F, Berg G, Blettner M. Validation of self-reported cellular phone use. J Expo Sci Environ Epidemiol. 2004; 14(3):245-8.

20. Inyang I, Benke G, Morrissey J, McKenzie R, Abramson M: How well do adolescents recall use of mobile telephones? Results of a validation study. BMC Med Res Methodol. 2009, 9:36.

21. A Common Sense Media Research Study. Zero to Eight Children's Media Use in America 2013. https://www.commonsensemedia.org/research (Accessed on 18.12.2016).

22. Davie R, Panting C, Charlton T. Mobile phone ownership and usage among pre-adolescents. Telematics and Informatics 2004; 21(4):359-73.

23. Khorseva NI, Grigor'ev Iu G, Gorbunova NV. Psychophysiological indicators for children using mobile phones. Communication 2. Results of four-year monitoring. Radiatsionnaia Biologiia, Radioecologiia 2011; 51(5):617-23.

24. Mollica CM, Maruff P, Collie A, Vance A. Repeated assessment of cognition in children and the measurement of performance change. Child Neuropsychology 2005; 11(3):303-10.

25. Regel SJ, Achermann P. Cognitive performance measures in bioelectromagnetic research–critical evaluation and recommendations. Environ Health 2011; 10(1):10.

26. Valentini E, Ferrara M, Presaghi F, De Gennaro L, Curcio G. Systematic review and meta-analysis of psychomotor effects of mobile phone electromagnetic fields. Occup Environ Med. 2010, 67(10):708-16.

27. Verrender A, Loughran S, Dalecki A, McKenzie R, Croft R. Pulse modulated radiofrequency exposure influences cognitive performance. Int J Radiat Biol. 2016:1.

28. Bhatt CR, Redmayne M, Abramson MJ, Benke G. Instruments to assess and measure personal and environmental radiofrequency-electromagnetic field exposures. Australas Phys Eng Sci Med. 2015; 39:29-42.

29. Ng TP, Lim ML, Niti M, Collinson S. Long-term digital mobile phone use and cognitive decline in the elderly. Bioelectromagnetics 2012; 33(2):176-85.

Chapter 7. Discussion

This project was carried out to inform and strengthen the knowledge of RF-EMF exposure assessment vis-à-vis mobile and cordless phones and other RF-EMF emitting sources and associated health effects. Therefore, my thesis addressed the two high priority RF-EMF research agendas of the WHO (50) – performance of RF-EMF exposure assessments (chapters 2, 3, 4 and 5) and prospective cohort epidemiological study in children (chapter 6).

The thesis commenced with the review of literature (chapter 2) related to the tools that have been or can be used in the objective assessment of RF-EMF exposure for current and future epidemiological studies. Then I used some of these tools to evaluate environmental and micro-environmental personal RF-EMF exposure assessments (82, 93, 94). The micro-environment is regarded as spaces where members of the general public typically spend time during their everyday life, such as homes, offices, shopping centres, transportation, etc. The micro-environmental personal exposure characterises the personal RF-EMF exposures, as experienced by a particular person for that specific space and time (95, 96). I also measured environmental and personal far-field RF-EMF exposures in children. Finally, this thesis also evaluated cognitive health outcomes of primary school children in relation to their MP and CP usage.

This chapter firstly reviews the key findings of the thesis. Secondly, the novel aspects and limitations of the thesis are discussed. Thirdly, the recommendations for the future research are presented and policy implications of the findings discussed. Finally, overall conclusions of the thesis are presented.

7.1. Review of main findings

7.1.1. Instruments to measure personal and environmental RF-EMF exposures

The instruments that are used to objectively quantify personal and environmental RF-EMF exposures fall broadly into two groups: mobile phone-based and exposimeters, which measure near-field exposures and far-field exposures, respectively. These tools provide measurements with high accuracy in the field of RF-EMF exposure assessment, which has been a real challenge in epidemiological research. The utilization of these tools will therefore enable reduction in misclassification of exposure in epidemiological studies.

The review found three smartphone-based applications (apps): XMobiSens™ (97); Tawkon™ (98), and Quanta Monitor™ (99); these only run on Android™-based phones and tablets to evaluate RF-EMF exposures from these near-field RF-EMF sources. There were also two earlier MP-based instruments: Software Modified Phone (SMP) (100, 101) and Hardware Modified Phone (HMP) (102). These instruments allow a MP to provide the functionalities of a phone and a near-field RF-EMF dosimeter. Since these apps are not compatible with iPhones® (iOS), there is still a need for similar apps for iPhone exposure assessment.

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XMobiSens™ provides data on some of the useful parameters, such as number and duration of voice calls, laterality of usage, phone received power, number of SMS, etc. (97), which are useful surrogates for RF-EMF exposure. The app has recently been validated and found to be useful for epidemiological studies (97). Tawkon™ only provides data on duration of calls (98), therefore has limited use in epidemiological research. The useful parameters estimated by Quanta Monitor™ are average power density ($\mu W/m^2$) for phone networks and Wi-Fi, cumulative power density ($\mu Wh/m^2$) and exposure duration (99). Even though this tool seems to be useful, it lacks an independent validation.

SMPs store data on number and duration of calls, output power level, cumulative emitted power, etc. (100, 101). HMPs collect data on number and duration of calls, power output, power fluctuations, phone tilts and rotations, etc. (102). Though these proxy measures of MP RF-EMF exposure are important information, SMP and HMP seem to offer limited applicability these days as a majority of people in Western countries use smart phones.

Environmental and personal far-field RF-EMF exposures have been evaluated using the body-worn exposimeter(s) (69, 70, 72, 73, 103, 104). The exposimeters that are mostly in current use are: EME Spy 200™ (105), ESM 140™ (106), Narda exposimeters (Nardalert S3™, RadMan™ and RadMan XT™) (107), ExpoM-RF™ (108), and personal distributed exposimeters (PDEs) (93, 109). EME Spy series, ESM 140™ and ExpoM-RF™ have been used to assess RF-EMF exposures in multiple frequency bands ranging from 87 MHz (FM radio) to 5.8 GHz (WiMax) (28). Narda exposimeters have been particularly used for assessing occupational RF-EMF exposures (110, 111) as they cover a much broader frequency range (100 kHz–50 GHz) (28). The PDEs (prototype versions) only cover two frequency bands of 900 MHz downlink and 2.4 GHz (28). These instruments are not yet commercially available, as they are still under development.

Currently available instruments for assessing RF-EMF exposure provide objective RF-EMF exposure data. Therefore, these instruments offer numerous potential benefits to epidemiological studies compared to traditionally used proxy measures of RF-EMF exposure such as questionnaires, billing records, distance to mobile phone base station(s)/RF-antenna, etc.

7.1.2. Measuring personal exposure from 900 MHz mobile phone base stations

This study employed a PDE to measure personal exposure from 900 MHz downlink frequency band across 34 microenvironments (n=17 each in Australia and Belgium) (93). The study established that it was feasible to measure personal RF-EMF exposures with PDEs. Furthermore, this also allowed a comparison of exposures across similar microenvironments located in two countries.

The RF-EMF exposures (900 MHz downlink) across most of the microenvironments in Australia were found to be much lower than those across the microenvironments in Belgium (93). The study found that the exposures across urban microenvironments were higher than those in the rural or suburban microenvironments (93). Similarly, the RF-EMF exposure levels across the outdoor were higher than those for indoor microenvironments. The exposure levels found in this study were compared to those reported by previous studies conducted across Europe, including Belgium (72-74). However, the most novel approach of this study was that it employed three body-distributed RF-EMF antennas that resulted in the measurements with minimum measurement uncertainties related to body shielding (see chapter 3).

The measurements reported in this study were far below the general public reference levels – the mean exposures in Australia were 0.02–3.6% of the ARPANSA reference level, whereas those in Belgium were 0.03–2.7% of the ICNIRP reference level. It should be noted that a direct comparison between environmental RF-EMF exposures and the ICNIRP recommendations may not be very useful in terms of possible long-term low level RF-EMF exposure effects on health. The current ICNIRP guidelines were developed mainly to protect humans from the short-term established health effects of RF-EMF exposures, such as tissue heating, stimulation of peripheral nerves and muscles, and shocks and burns caused by touching conducting objects (112). Though the ICNIRP included safety factors, they necessarily do not cover possible health or biological effects related to long-term low-level RF-EMF exposures (113). In the case of potential long-term effects of RF-EMF exposure, such as an increased risk of cancer, ICNIRP concluded that available data were insufficient to provide a basis for setting exposure restrictions (32).

7.1.3. Assessment of personal exposure from RF-EMFs

This study assessed personal exposure from various RF-EMF sources (88 MHz-5.8 GHz) across 38 microenvironments (19 each in Australia and Belgium), with two on-body calibrated ExpoM-RFs^{TM}. This work therefore accounted for the measurement uncertainties related to body shielding caused by single exposimeters (94). The concurrent use of two on-body calibrated exposimeters provided much more accurate exposure data compared to those provided by a single non-on-body calibrated exposimeter (94).

The study allowed a comparison of the RF-EMF exposure levels measured for one site in each of several selected microenvironments in the two countries. The same human subject took part in an on-body calibration of the exposimeter and performed subsequent data collection (chapter 4). The study showed that it was feasible to employ two exposimeters concurrently to estimate personal RF-EMF exposures.

The personal exposures measured across urban microenvironments were higher than those compared to rural or suburban microenvironments. Mobile phone base downlink exposures contributed the largest share to total exposures. Also, the exposure levels across outdoor microenvironments were higher than those compared to indoor microenvironments. These findings are similar to those shown by other studies (69, 72, 75, 114), including my previous study (93).

7.1.4. RF-EMF exposures in kindergarten children

This study described environmental and personal RF-EMF exposures in kindergarten children. The findings were based on the environmental RF-EMF exposures measured in 20 kindergartens in Melbourne, Australia. Also, 10 children (age 3-5 years old) attending five kindergartens provided participated in personal RF-EMF exposure measurements (82).

Of the 16 frequency bands (88 MHz–5.8 GHz) measured, the largest source of RF-EMF exposure was attributed to mobile phone base stations, particularly 900 MHz downlink (82). These measurements are comparable to recent school RF-EMF measurements (84), and the measurements of micro-environmental personal exposures reported here, both in Australia (93, 94). Wi-Fi exposure was found to be very low compared with mobile phone base station exposure. However, Wi-Fi exposure in schools could be higher due to the use of Wi-Fi connected devices by students or staff (115). Environmental RF-EMF exposure levels at kindergartens located near base stations (i.e. <300 m) were higher compared with those further away (i.e. >300 m). The highest values of all frequency-band specific exposures were < 1% of the ARPANSA reference levels for general populations. However, as stated above, the reference levels are mainly developed to protect humans from RF-EMF exposure related heating effects, and therefore, may not necessarily protect from long-term RF-EMF exposures.

It should be borne in mind that the results of this study are limited to far-field RF-EMF exposures. The near-field RF-EMF exposures due to the use of Wi-Fi enabled devices (e.g. MP, computers, tablets, etc.) are likely to be higher compared to far-field exposures. The exposure situations for children in homes may differ due to their use of other RF-EMF emitting devices by them and other family members. An active router connected to Wi-Fi enabled devices sends RF-EMF signals more often compared to an idle router (84, 115).

7.1.5. Use of MP and CP and change in cognitive function

This study provides results from personal use of phones amongst children and its subsequent effects on their psychological development. This is a prospective cohort epidemiological study, which supports one of the high priority RF-EMF research agendas recommended by the WHO (50). The cross-sectional findings on the effects of the children's use of mobile and cordless phones in cognitive functions were published (18). The current study evaluated possible longitudinal associations between the use of MPs and CPs in a cohort of primary school children and effects on their cognitive function over a one year period.

The study showed that children's ownership/use of a MP increased from baseline to follow-up. In contrast, the use of a CP at home remained fairly the same. The ownership/usage of MPs found in this sample of Australian children was low, but comparable to rates reported elsewhere such as in the US and across several European countries (16, 20, 21, 116-118). The results indicated that a lesser proportion of primary school children owned/used a MP compared to secondary school children as found in the MoRPhEUS study (15). The increase in MP usage was significantly associated with larger reduction in response time for the response inhibition task, smaller reduction in the number of total errors for spatial problem solving and larger increase in response time for a Stroop interference task. However, the overall findings suggested that limited evidence that changes in the use of MPs/CPs in primary school children were associated with changes in cognitive function. A longitudinal cohort study of secondary school children showed that increase in MP usage was significantly associated with slower response time for signal detection task, but quicker working memory task (15).

There is no well-known mechanism regarding how MP/CP RF-EMF exposure affects cognitive function. One of the hypotheses is related to the potential role of temperature elevation (thermal effect) of RF-EMF exposure (52). Furthermore, RF-EMF may change electrical field potentials generated by cells, and excitability of neurons resulting in polarised membranes (53). In addition to RF-EMF exposure, there are numerous behavioural and social factors that potentially affect children's cognition (54). Though my study accounted for some of them, such as gaming, computer and Internet use, I acknowledge that the children's cognition might have been also influenced by other unmeasured behavioural and social factors.

Human learning and memory processes are controlled by the hippocampus, which is anatomically situated within the temporal lobe of the brain. If RF-EMF exposure could potentially affect the learning and memory, this particular region should be influenced by the absorption of RF-EMF exposure. Interestingly, it has been demonstrated that the temporal lobe is the area where more than 50% of the MP-associated RF-EMF exposure is absorbed (119). Therefore, it could be hypothesised that the RF-EMF absorption that takes place in the temporal lobes of the brain due to MP usage may influence human cognitive function. However, it is still unclear exactly how RF-EMF exposure to hippocampus could affect cognitive tasks such as those related to learning and memory.

7.2. Novelty of the thesis

In this thesis, I have applied the state-of-the art objective tools to assess the environmental and personal RF-EMF exposures with novel approaches while performing exposure measurements.

Chapter 3 presented the first demonstration of how an on-body calibrated PDE could be used to measure personal exposure from 900 MHz downlink band across various microenvironments. Unlike a single receiving antenna used in the most of the body-worn exposimeters, the PDE had three antennas (two anterior, and one posterior) that were distributed over the body. This was done to minimise measurement uncertainties related to body shielding, which were generally encountered in the conventional approach to deployment of exposimeters (28, 89).

Chapter 4 demonstrated the first effort towards the assessment of far-field microenvironmental RF-EMF exposures from multiple sources across different microenvironments using a pair of on-body calibrated exposimeters. Furthermore, my evaluation of the performance of the exposimeters by using cross-talk measurements allowed me to interpret the data collected. Measurements were also extended to 2.6 GHz, WiMaX 3.5 GHz, and ISM 5.8 GHz bands, which were not considered in previous studies.

Chapters 3 and 4 discussed how the same human subject was available for on-body calibration and subsequent field measurements in Belgium and Australia. This allowed me to make a valid and direct comparison of exposure levels across similar microenvironments of two countries. This contrasts to previous studies as either the measurement instruments or approaches to data collection were different (72). For the first time, personal microenvironmental RF-EMF exposure levels were reported for Australia.

My kindergarten study (chapter 5) presented the first findings on total environmental (indoor and outdoor) and children's RF-EMF exposures in kindergartens. Furthermore, this chapter provided the first evidence of how far-field personal RF-EMF exposures could be directly measured in kindergarten children. The chapter also provided proof-of-concept to carry out RF-EMF exposure assessment amongst pre-school children for future RF-EMF epidemiological studies.

Finally, findings of a longitudinal association of the use of mobile and cordless phones and change in cognition in a representative community-based sample of primary school children were reported (see chapter 6). The study involved a larger number of cognitive tasks compared to similar studies conducted elsewhere (20, 21).

7.3. Policy Implications and Recommendations

The knowledge of RF-EMF exposures in human populations and potential health effects provides the basis for formulating evidence-based RF-EMF policies. Therefore, it is useful to update assessments of RF-EMF exposures and population health outcomes on a regular basis since human exposure sources and situations have been changing over time. The monitoring of RF-EMF exposures not only helps in understanding the existing exposure situations, but also facilitates carrying out risk assessments and interpreting RF-EMF epidemiological research. This could potentially help in risk management and risk communication processes and policies to RF-EMF. The future RF-EMF policies should therefore consider a RF-EMF exposure monitoring program as essential.

The issue of children's RF-EMF exposures from various RF-EMF sources, particularly mobile and cordless phones, and mobile phone base stations has been important due to their greater cumulative exposure and potential long-term health effects. There is still an ongoing scientific debate regarding the extent of RF-EMF exposure of children compared to adults (17, 46-48, 119). As a result of this, different countries have been adopting their own policies and advisory responses regarding children's RF-EMF exposures (17). In Australia, ARPANSA adopts a policy of the precautionary principle – i) the concerned individuals should choose to limit their own or their children's RF-EMF exposure, ii) parents should encourage their children to limit RF-EMF exposure (17).

My kindergarten study findings may have policy implications regarding the siting of mobile phone base stations, particularly near to kindergartens or schools in view of likely continuous base station exposures. The mobile phone base stations closer to kindergartens and schools resulted in higher exposures to children compared to those situated further from the base stations. Furthermore, the low far-field Wi-Fi exposures found in kindergartens may help placate the worries of those parents who have concerns regarding their children's exposure from Wi-Fi routers at preschools.

The ExPOSURE study participants had low MP usage. Therefore, the extent of possible cognitive function effects in the child population characterised by higher MP use requires further research. The study demonstrated no indication of consistent or substantial harmful effects on children's cognitive function related to MP/CP usage. This is a reassuring finding *per se*, though my study has several limitations, including low use of MP and relatively short follow-up time (i.e. 1 year).

The following recommendations are based on the findings in this thesis:

1. Objective assessment of RF-EMF exposures should be preferably conducted in epidemiological studies, as currently available tools provide better measures of RFEMF exposures compared to the previously used proxy measures of exposures (e.g. questionnaires, billing records, distance to mobile phone base stations, etc.).
2. An independent scientific validation of Quanta Monitor™ (MP-based app) is needed to assess the agreement between the values of exposure parameters provided by the app and those provided by other similar validated smart phone-based tools (e.g. XMobiSens™). Such assessment would provide valuable information regarding their suitability in future RF-EMF epidemiological studies.
3. It is important that future exposure assessment devices should have the capability to objectively measure RF-EMF exposures from iPhones®, cordless phones and laptop devices.

4. Exposimeters need to be small and light-weight for convenience reasons. Furthermore, they should also have longer battery life and be able to measure a larger number of frequency bands with lower detection limits. This would enable long-term measurements of exposures from various RF-EMF sources in different geographical contexts.
5. Whole body distributed exposimeters, such as the PDE, require further development to be more user-friendly, and should preferably be able to accommodate the simultaneous measurement of multiple frequency bands.
6. It is clear that the RF-EMF exposure assessment applying a pair of on-body calibrated exposimeters has benefits over the use of a single non-on-body calibrated exposimeter in minimizing body-shielding related measurement uncertainties. Therefore, I recommend applying on-body calibrated exposimeters in future studies, whenever possible.
7. Future studies should also consider performing repeated (i.e. more than two measurements) personal RF-EMF exposure measurements along different paths in the same microenvironment to examine if they provide the similar RF-EMF exposure levels.
8. Environmental and personal RF-EMF exposure assessments should be continued in future in order to monitor change in the RF-EMF exposure levels and ascertain the different sources of RF-EMF exposures.
9. The fact that environmental RF-EMF exposure levels in kindergarten were greater than the kindergarten children’s personal exposure levels should be interpreted cautiously. This often appears to be the case because the human body shields some of the ambient RF-EMF that goes unmeasured by the personal RF-EMF exposure measurement devices (e.g. ExpoM-RF) placed on the other side of the body.

10. Future longitudinal cohort studies in children may consider a longer follow-up period (> 1 year) with multiple waves of surveys, while assessing the effects of MP and CP use on cognitive development, if possible. These studies should also use objective measures of MP exposure (at least in the sub-sample of children), whenever possible. This will improve exposure assessment of MP RF-EMF exposure.
11. Future RF-EMF epidemiological studies should ideally perform an integrated exposure assessment of both near-field (e.g. MP, CP, laptop, etc.) and far-field RF EMF exposures (mobile phone base stations, Wi-Fi hotspots/routers, radio/TV signals etc.). This would provide a more holistic description of RF-EMF exposure.

Chapter 8. Conclusions

To minimise exposure misclassification for epidemiological research, it is important that the RF-EMF exposures should be measured with the best available objective tools that provide data on RF-EMF exposures from near-field and far-field RF-EMF sources. RF-EMF researchers should validate and use these tools, and provide relevant recommendations regarding the appropriateness, limitations and requirements vis-à-vis future epidemiological studies.

Of all far-field RF-EMF exposure sources (88 MHz – 5.8 GHz), mobile phone base stations have been identified as one of the largest contributors to environmental and personal RF-EMF exposures. Even though these exposure are typically far less than ICNIRP/ARPANSA reference levels, a periodic assessment of the exposures from mobile phone base stations becomes relevant, particularly in view of any potential health effects of long-term RF-EMF exposures. This would also inform the general public and policy makers regarding existing RF-EMF exposures in different human environments by comparing them to the ICNIRP/ARPANSA recommendations, providing the permitted/recommended exposures remain the same. This would also subsequently help policy makers formulate more evidence-based RF-EMF policies in regard to human RF-EMF exposures.

The findings in this thesis indicate that for the most part, children's RF-EMF exposure in kindergartens which are not using Wi-Fi enabled devices during sessions is dependent on the distance to the nearby mobile phone base station(s). Therefore, future deployment of mobile phone base stations in the surroundings of preschools or schools should take this into consideration.

This thesis also found that a lower proportion of primary school children in Australia own/use MPs than CPs. Phone usage in the children was shown to be not affecting most of their cognitive tasks. This work is the best published effort to detect effects of MP/CP use on cognitive function in young children. It was longitudinal, included multiple measures of cognition, and had a moderately large sample. The study found no sign of consistent or substantial detriment on children's cognition. This is reassuring, although my findings are not the final conclusion on the matter. The finding that increased use of phones was associated with improved cognitive function in some instances – the thesis did not put much weight on this, and it may be a chance finding given the large number of associations that were tested. Further research with better measures of use of phones, including exposure estimates provided by apps (such as XMobisens™ and Quanta Monitor™) would be worth carrying out. This could largely overcome the potential issue of MP exposure misclassification.

References

1. The first mobile phone call was placed 40 years ago today: Fox News. [cited 2016.12.16]. Available from: http://www.foxnews.com/tech/2013/04/03/first-mobile-phone-call-was-placed-40-years-ago-today.html?refresh=true.
2. Australia's mobile decade: Australian Mobile Telecommunications Association. [cited 2016.12.16]. Available from: http://www.mobilemuster.com.au/media/107666/australia_s_mobile_decade.pdf.
3. ICT Facts and Figures. [cited 2016.12.16]. Available from: https://www.itu.int/en/ITU-D/Statistics/Documents/facts/ICTFactsFigures2015.pdf.
4. Allen S. Radiofrequency field measurements and hazard assessment. J Radiol Prot. 1991;11(1):49-62.
5. Bhalla MR, Bhalla AV. Generations of mobile wireless technology: A survey. International Journal of Computer Applications. 2010;5(4).
6. Australia's mobile decade. 10 years of consumer insights into mobile use and recycling: 2005-2015. [cited 2016.12.16]. Available from: http://www.mobilemuster.com.au/media/107666/australia_s_mobile_decade.pdf.
7. Australian Mobile Telecommunications Association. [cited 2016.12.16]. Available from: https://www.accc.gov.au/system/files/4%20AMTA,%20Ten%20years%20of%20GSM%20in%20Australia,%20www.amta.gov.au.pdf.
8. Pereira V, Sousa, T. (editor). Evolution of Mobile Communications: from 1G to 4G. The 2nd International Working Conference on Performance Modelling and Evaluation of hetrogeneous Networks; West Yorkshire, UK. 2004.

9. Australian Phone Networks and Frequencies Explained. [cited 2016.12.16]. Available from: https://www.whistleout.com.au/MobilePhones/Guides/Will-my-phone-work-in-Australia-carrier-network-frequencies.
10. Berg-Beckhoff G, Blettner M, Kowall B, Breckenkamp J, Schlehofer B, Schmiedel S, et al. Mobile phone base stations and adverse health effects: phase 2 of a cross-sectional study with measured radio frequency electromagnetic fields. Occup Environ Med. 2009;66(2):124-130.
11. Ha M, Im H, Lee M, Kim HJ, Kim B-C, Gimm Y-M, et al. Radio-frequency radiation exposure from AM radio transmitters and childhood leukemia and brain cancer. Am J Epidemiol. 2007;166(3):270-279.
12. Redmayne M, Smith E, Abramson MJ. The relationship between adolescents' well-being and their wireless phone use: a cross-sectional study. Environ Health 2013;12:90.
13. Rothman KJ, Chou CK, Morgan R, Balzano Q, Guy AW, Funch DP, et al. Assessment of cellular telephone and other radio frequency exposure for epidemiologic research. Epidemiology 1996;7(3):291-298.
14. Foster KR, Moulder JE. Wi-Fi and health: review of current status of research. Health Phys. 2013;105(6):561-575.
15. Thomas S, Benke G, Dimitriadis C, Inyang I, Sim M, Wolfe R, et al. Use of mobile phones and changes in cognitive function in adolescents. Occup Environ Med. 2010;67(12):861-866.
16. Redmayne M. New Zealand adolescents' cellphone and cordless phone user-habits: are they at increased risk of brain tumours already? A cross-sectional study. Environ Health 2013;12:5.

17. Redmayne M. International policy and advisory response regarding children's exposure to radio frequency electromagnetic fields (RF-EMF). Electromagn Biol Med.2015:1-9.

18. Redmayne M, Smith CL, Benke G, Croft RJ, Dalecki A, Dimitriadis C, et al. Use of mobile and cordless phones and cognition in Australian primary school children: a prospective cohort study. Environ Health 2016;15(1):26.

19. Kabali HK, Irigoyen MM, Nunez-Davis R, Budacki JG, Mohanty SH, Leister KP, et al. Exposure and Use of Mobile Media Devices by Young Children. Pediatrics 2015;136(6):1044-1050.

20. Schoeni A, Roser K, Röösli M. Memory performance, wireless communication and exposure to radiofrequency electromagnetic fields: A prospective cohort study in adolescents. Environ Int. 2015;85:343-351.

21. Guxens M, Vermeulen R, van Eijsden M, Beekhuizen J, Vrijkotte TG, van Strien RT, et al. Outdoor and indoor sources of residential radiofrequency electromagnetic fields, personal cell phone and cordless phone use, and cognitive function in 5-6 years old children. Environ Res. 2016;150:364-374.

22. Byun Y-H, Ha M, Kwon H-J, Hong Y-C, Leem J-H, Sakong J, et al. Mobile phone use, blood lead levels, and attention deficit hyperactivity symptoms in children: a longitudinal study. PLoS One 2013;8(3):e59742.

23. Human Exposure to Radiofrequency Electromagnetic Fields. Federal Communications Commission 2013. p. 33634-53. [cited 2017.1.16].

24. Children's use of mobile phones – A special report 2014. [cited 2017.1.16]. Available from: http://www.gsma.com/publicpolicy/wp-content/uploads/2012/03/GSMA_Childrens_use_of_mobile_phones_2014.pdf.

25. Houghton S, Hunter SC, Rosenberg M, Wood L, Zadow C, Martin K, et al. Virtually impossible: limiting Australian children and adolescents daily screen based media use. BMC Public Health 2015;15(1):1.
26. Vecchia P, Matthes R, Ziegelberger G, Lin J, Saunders R, Swerdlow A. Exposure to high frequency electromagnetic fields, biological effects and health consequences (100 kHz-300 GHz). International Commission on Non-Ionizing Radiation Protection 2009.
27. Markov M, Grigoriev YG. Wi-Fi technology--an uncontrolled global experiment on the health of mankind. Electromagn Biol Med. 2013;32(2):200-208.
28. Bhatt CR, Redmayne M, Abramson MJ, Benke G. Instruments to assess and measure personal and environmental radiofrequency-electromagnetic field exposures. Australas Phys Eng Sci Med. 2016;39(1):29-42.
29. Lin JC. Dosimetric comparison between different quantities for limiting exposure in the RF band: rationale and implications for guidelines. Health Phys. 2007;92(6):547-553.
30. Roser K, Schoeni A, Bürgi A, Röösli M. Development of an RF-EMF Exposure Surrogate for Epidemiologic Research. Int J Environ Res Public Health 2015;12(5):5634-5656.
31. Cardis E, Deltour I, Mann S, Moissonnier M, Taki M, Varsier N, et al. Distribution of RF energy emitted by mobile phones in anatomical structures of the brain. Phys Med Biol. 2008;53(11):2771.
32. ICNIRP guidelines for limiting exposure to time-varying electric, magnetic and electromagnetic fields (up to 300 GHz). Health Phys. 1998;74(4):494-522.
33. Radiation Protection Standard. Maximum Exposure Levels to Radiofrequency Fields - 3 kHz to 300 GHz. Radiation Protection Series Publication No. 3: the Australian

Radiation Protection and Nuclear Safety Agency; 2002. p. 1-128.

34. Eurobarometer TNS Opinion Social, Eurobarometer 73.3, Electromagnetic Fields, 2010. [cited 2017.2.16]. Available from: http://ec.europa.eu/public_opinion/archives/ebs/ebs_347_en.pdf.
35. Hardell L, Mild KH, Carlberg M. Case-control study on the use of cellular and cordless phones and the risk for malignant brain tumours. Int J Radiat Biol. 2002;78(10):931-936.
36. Hardell L, Carlberg M, Mild KH. Case-control study of the association between the use of cellular and cordless telephones and malignant brain tumors diagnosed during 2000-2003. Environ Res. 2006;100(2):232-241.
37. Hardell L, Carlberg M, Hansson Mild K. Case-control study on cellular and cordless telephones and the risk for acoustic neuroma or meningioma in patients diagnosed 2000-2003. Neuroepidemiology 2005;25(3):120-128.
38. Lahkola A, Auvinen A, Raitanen J, Schoemaker MJ, Christensen HC, Feychting M, et al. Mobile phone use and risk of glioma in 5 North European countries. Int J Cancer. 2007;120(8):1769-1775.
39. INTERPHONE Study Group. Brain tumour risk in relation to mobile telephone use: results of the INTERPHONE international case-control study. Int J Epidemiol. 2010;39(3):675-694.
40. Cardis E, Armstrong BK, Bowman JD, Giles GG, Hours M, Krewski D, et al. Risk of brain tumours in relation to estimated RF dose from mobile phones: results from five Interphone countries. Occup Environ Med. 2011;68(9):631-640.
41. Grell K, Frederiksen K, Schuz J, Cardis E, Armstrong B, Siemiatycki J, et al. The Intracranial Distribution of Gliomas in Relation to Exposure From Mobile Phones: Analyses From the INTERPHONE Study. Am J Epidemiol. 2016;184(11):818-828.

42. Coureau G, Bouvier G, Lebailly P, Fabbro-Peray P, Gruber A, Leffondre K, et al. Mobile phone use and brain tumours in the CERENAT case-control study. Occup Environ Med. 2014;71(7):514-522.
43. Frei P, Poulsen AH, Johansen C, Olsen JH, Steding-Jessen M, Schüz J. Use of mobile phones and risk of brain tumours: update of Danish cohort study. BMJ 2011;343:d6387.
44. Schüz J, Steding-Jessen M, Hansen S, Stangerup S-E, Cayé-Thomasen P, Poulsen AH, et al. Long-term mobile phone use and the risk of vestibular schwannoma: a Danish nationwide cohort study. Am J Epidemiol. 2011;174(4):416-422.
45. Baan R, Grosse Y, Lauby-Secretan B, El Ghissassi F, Bouvard V, Benbrahim-Tallaa L, et al. Carcinogenicity of radiofrequency electromagnetic fields. Lancet Oncol. 2011;12(7):624-626.
46. Gandhi OP. Yes the Children Are More Exposed to Radiofrequency Energy From Mobile Telephones Than Adults. IEEE Acess 2015;3:985-988.
47. Foster KR, Chou C-K. Are children more exposed to radio frequency energy from mobile phones than adults? IEEE Access 2014;2:1497-1509.
48. Morris RD, Morgan LL, Davis D. Children absorb higher doses of radio frequency electromagnetic radiation from mobile phones than adults. IEEE Access 2015;3:2379-2387.
49. Kheifets L, Repacholi M, Saunders R, Van Deventer E. The sensitivity of children to electromagnetic fields. Pediatrics 2005;116(2):e303-e313.
50. van Deventer E, van Rongen E, Saunders R. WHO research agenda for radiofrequency fields. Bioelectromagnetics 2011;32(5):417-421.

51. Abramson MJ, Benke GP, Dimitriadis C, Inyang IO, Sim MR, Wolfe RS, et al. Mobile telephone use is associated with changes in cognitive function in young adolescents. Bioelectromagnetics 2009;30(8):678-686.

52. Smythe JW, Costall B. Mobile phone use facilitates memory in male, but not female, subjects. Neuroreport 2003; 14 (2): 243-246.

53. Stewart Report. Sir William Stewart (Chairman) Mobile Phones and Health: A report from the Independent Expert Group on Mobile Phones, Chilton, IEGMP Secretariat (May 2000). Available at http://disi.unal.edu.co/~gjhernandezp/STEMETICS/ReportOfTheIndependentExpertGroupOnMobilePhones.pdf

54. Billieux J. Problematic Use of the Mobile Phone: A Literature Review and a Pathways Model. Current Psychiatry Reviews 2012; 8: 000-000.

55. Klaps A, Ponocny I, Winker R, Kundi M, Auersperg F, Barth A. Mobile phone base stations and well-being--A meta-analysis. Sci Total Environ. 2016;544:24-30.

56. Valberg PA, van Deventer TE, Repacholi MH. Workgroup report: base stations and wireless networks-radiofrequency (RF) exposures and health consequences. Environ Health Perspect. 2007;115(3):416-424.

57. Thomas S, Kuhnlein A, Heinrich S, Praml G, Nowak D, von Kries R, et al. Personal exposure to mobile phone frequencies and well-being in adults: a cross-sectional study based on dosimetry. Bioelectromagnetics 2008;29(6):463-470.

58. Heinrich S, Thomas S, Heumann C, von Kries R, Radon K. Association between exposure to radiofrequency electromagnetic fields assessed by dosimetry and acute symptoms in children and adolescents: a population based cross-sectional study. Environ Health 2010;9(1):75.

59. Hutter H, Moshammer H, Wallner P, Kundi M. Subjective symptoms, sleeping problems, and cognitive performance in subjects living near mobile phone base stations. Occup Environ Med. 2006;63(5):307-313.

60. Gómez-Perretta C, Navarro EA, Segura J, Portolés M. Subjective symptoms related to GSM radiation from mobile phone base stations: a cross-sectional study. BMJ Open 2013;3(12):e003836.

61. Berg-Beckhoff G, Blettner M, Kowall B, Breckenkamp J, Schlehofer B, Schmiedel S, et al. Mobile phone base stations and adverse health effects: phase 2 of a cross-sectional study with measured radio frequency electromagnetic fields. Occup Environ Med. 2009;66(2):124-130.

62. Röösli M, Frei P, Mohler E, Hug K. Systematic review on the health effects of exposure to radiofrequency electromagnetic fields from mobile phone base stations. Bull World Health Organ. 2010;88(12):887-896f.

63. Havas M. Radiation from wireless technology affects the blood, the heart, and the autonomic nervous system. Rev Environ Health. 2013;28(2-3):75-84.

64. The World Health Organization. Electromagnetic fields and public health. Electromagnetic hypersensitivity. [cited 2017.1.23]. Available from: http://www.who.int/peh-emf/publications/facts/fs296/en/.

65. van Moorselaar I, Slottje P, Heller P, van Strien R, Kromhout H, Murbach M, et al. Effects of personalised exposure on self-rated electromagnetic hypersensitivity and sensibility – A double-blind randomised controlled trial. Environ Int. 2017;99:255-262.

66. Inyang I, Benke G, Mckenzie R, Abramson M. Comparison of measuring instruments for radiofrequency radiation from mobile telephones in epidemiological studies:

Implications for exposure assessment. J Exposure Sci Environ Epidemiol. 2008;18(2):134-141.

67. Vrijheid M, Armstrong BK, Bedard D, Brown J, Deltour I, Iavarone I, et al. Recall bias in the assessment of exposure to mobile phones. J Exposure Sci Environ Epidemiol. 2009;19(4):369-381.

68. Vrijheid M, Deltour I, Krewski D, Sanchez M, Cardis E. The effects of recall errors and of selection bias in epidemiologic studies of mobile phone use and cancer risk. J Exposure Sci Environ Epidemiol. 2006;16(4):371-384.

69. Bolte JFB, Eikelboom T. Personal radiofrequency electromagnetic field measurements in the Netherlands: Exposure level and variability for everyday activities, times of day and types of area. Environ Int. 2012;48(0):133-142.

70. Frei P, Mohler E, Neubauer G, Theis G, Burgi A, Fröhlich J, et al. Temporal and spatial variability of personal exposure to radio frequency electromagnetic fields. Environ Res. 2009;109(6):779-785.

71. Gajšek P, Ravazzani P, Wiart J, Grellier J, Samaras T, Thuróczy G. Electromagnetic field exposure assessment in Europe radiofrequency fields (10 MHz-6 GHz). J Exposure Sci Environ Epidemiol. 2015;25(1):37-44.

72. Joseph W, Frei P, Roösli M, Thuróczy G, Gajšek P, Trcek T, et al. Comparison of personal radio frequency electromagnetic field exposure in different urban areas across Europe. Environ Res. 2010;110(7):658-663.

73. Urbinello D, Joseph W, Verloock L, Martens L, Röösli M. Temporal trends of radio-frequency electromagnetic field (RF-EMF) exposure in everyday environments across European cities. Environ Res. 2014;134:134-142.

74. Urbinello D, Joseph W, Huss A, Verloock L, Beekhuizen J, Vermeulen R, et al. Radio-frequency electromagnetic field (RF-EMF) exposure levels in different

European outdoor urban environments in comparison with regulatory limits. Environ Int. 2014;68c:49-54.

75. Vermeeren G, Markakis I, Goeminne F, Samaras T, Martens L, Joseph W. Spatial and temporal RF electromagnetic field exposure of children and adults in indoor micro environments in Belgium and Greece. Prog Biophys Mol Biol. 2013;113(2):254-263.
76. Viel JF, Tiv M, Moissonnier M, Cardis E, Hours M. Variability of radiofrequency exposure across days of the week: a population-based study. Environ Res. 2011;111(4):510-513.
77. Viel J-F, Cardis E, Moissonnier M, de Seze R, Hours M. Radiofrequency exposure in the French general population: Band, time, location and activity variability. Environ Int. 2009;35(8):1150-1154.
78. ACMA Communications reports 2013–14. [cited 2017.1.16]. Available from: http://www.acma.gov.au/theACMA/Library/Corporate-library/Corporate-publications/communications-report.
79. Rowley JT, Joyner KH. Comparative international analysis of radiofrequency exposure surveys of mobile communication radio base stations. J Exposure Sci Environ Epidemiol. 2012;22(3):304-315.
80. Henderson S, Bangay M. Survey of RF exposure levels from mobile telephone base stations in Australia. Bioelectromagnetics 2006;27(1):73-76.
81. Radio Frequency National Site Archive. [cited 2017.1.16]. Available from: http://www.rfnsa.com.au/nsa/index.cgi?type=logout.
82. Bhatt CR, Redmayne M, Billah B, Abramson MJ, Benke G. Radiofrequency-electromagnetic field exposures in kindergarten children. J Exposure Sci Environ Epidemiol. 2016 Oct 19. doi: 10.1038/jes.2016.55.

83. Juhász P, Bakos J, Nagy N, Jánossy G, Finta V, Thuróczy G. RF personal exposimetry on employees of elementary schools, kindergartens and day nurseries as a proxy for child exposures. Prog Biophys Mol Biol. 2011;107(3):449-455.

84. Karipidis K, Henderson S, Wijayasinghe D, Tjong L, Tinker R. Exposure to Radiofrequency Electromagnetic Fields From Wi-Fi in Australian Schools. Radiat Prot Dosimetry 2017 Jan 10. doi: 10.1093/rpd/ncw370.

85. Chapman S, Wutzke S. Not in our back yard: media coverage of community opposition to mobile phone towers–an application of Sandman's outrage model of risk perception. Aust N Z J Public Health 1997;21(6):614-620.

86. Mercer D. Hazards of decontextualised accounts of public perceptions of radio frequecy radiation (RFR) risk. Aust N Z J Public Health 1998;22(2):291.

87. Bolte JF, van der Zande G, Kamer J. Calibration and uncertainties in personal exposure measurements of radiofrequency electromagnetic fields. Bioelectromagnetics 2011;32(8):652-663.

88. Bolte JF. Lessons learnt on biases and uncertainties in personal exposure measurement surveys of radiofrequency electromagnetic fields with exposimeters. Environ Int. 2016;94:724-735.

89. Mann S. Assessing personal exposures to environmental radiofrequency electromagnetic fields. Comptes Rendus Physique 2010;11(9–10):541-555.

90. Iskra S, McKenzie R, Cosic I. Factors influencing uncertainty in measurement of electric fields close to the body in personal RF dosimetry. Radiat Prot Dosimetry 2010;140(1):25-33.

91. Iskra S, McKenzie R, Cosic I. Monte Carlo simulations of the electric field close to the body in realistic environments for application in personal radiofrequency dosimetry. Radiat Prot Dosimetry 2011;147(4):517-527.

92. Thielens A, Agneessens S, Verloock L, Tanghe E, Rogier H, Martens L, et al. On-body calibration and processing for a combination of two radio-frequency personal exposimeters. Radiat Prot Dosimetry 2015;163(1):58-69.

93. Bhatt CR, Thielens A, Redmayne M, Abramson MJ, Billah B, Sim MR, et al. Measuring personal exposure from 900MHz mobile phone base stations in Australia and Belgium using a novel personal distributed exposimeter. Environ Int. 2016;92:388-397.

94. Bhatt CR, Thielens A, Billah B, Redmayne M, Abramson MJ, Sim MR, et al. Assessment of personal exposure from radiofrequency-electromagnetic fields in Australia and Belgium using on-body calibrated exposimeters. Environ Res. 2016;151:547-563.

95. Röösli M, Frei P, Bolte J, Neubauer G, Cardis E, Feychting M, et al. Conduct of a personal radiofrequency electromagnetic field measurement study: proposed study protocol. Environ Health 2010;9:23.

96. Dürrenberger G, Fröhlich J, Röösli M, Mattsson MO. EMF monitoring-concepts, activities, gaps and options. Int J Environ Res Public Health 2014;11(9):9460-9479.

97. Goedhart G, Vrijheid M, Wiart J, Hours M, Kromhout H, Cardis E, et al. Using software‐modified smartphones to validate self-reported mobile phone use in young people: A pilot study. Bioelectromagnetics 2015;36(7):538-543.

98. Tawkon. [cited 2017.1.16]. Available from: http://tawkon.com/.

99. Cellraid Products. [cited 2017.1.16]. Available from: http://www.cellraid.com/products/.

100. Berg G, Schüz J, Samkange-Zeeb F, Blettner M. Assessment of radiofrequency exposure from cellular telephone daily use in an epidemiological study: German Validation study of the international case-control study of cancers of the brain-

INTERPHONE-Study. J Expo Anal Environ Epidemiol. 2005;15(3):217-224.

101. Vrijheid M, Mann S, Vecchia P, Wiart J, Taki M, Ardoino L, et al. Determinants of mobile phone output power in a multinational study: implications for exposure assessment. Occup Environ Med. 2009;66(10):664-671.

102. Inyang I, Benke G, McKenzie R, Abramson M. Use of hardware modified phones for exposure assessment in health studies in Australia: verification of compliance with standards. Australas Phys Eng Sci Med. 2009;32(2):62-67.

103. Urbinello D, Huss A, Beekhuizen J, Vermeulen R, Röösli M. Use of portable exposure meters for comparing mobile phone base station radiation in different types of areas in the cities of Basel and Amsterdam. Sci Total Environ. 2014;468-469:1028-1033.

104. Viel J-F, Clerc S, Barrera C, Rymzhanova R, Moissonnier M, Hours M, et al. Residential exposure to radiofrequency fields from mobile phone base stations, and broadcast transmitters: a population-based survey with personal meter. Occup Environ Med. 2009;66(8):550-556.

105. SATIMO. [cited 2017.1.16]. Available from: http://www.satimo.com/content/products.

106. Maschek Electronik. [cited 2017.1.16]. Available from: http://www.maschek.de/de/.

107. Narda Safety Test Solutions. [cited 2017.1.16]. Available from: http://www.narda-sts.us/products_main.php.

108. Introducing ExpoM - A personal RF exposure meter. [cited 2017.1.16]. Available from: http://www.fieldsatwork.ch/.

109. Thielens A, De Clercq H, Agneessens S, Lecoutere J, Verloock L, Declercq F, et al. Personal distributed exposimeter for radio frequency exposure assessment in real

environments. Bioelectromagnetics 2013;34(7):563-567.

110. Chauvin S, Gibergues ML, Wuthrich G, Picard D, Desreumaux JP, Bouillet JC. Occupational exposure to ambient electromagnetic fields of technical operational personnel working for a mobile telephone operator. Radiat Prot Dosimetry 2009;136(3):185-195.

111. Cooper TG, Allen SG, Blackwell RP, Litchfield I, Mann SM, Pope JM, et al. Assessment of occupational exposure to radiofrequency fields and radiation. Radiat Prot Dosimetry 2004;111(2):191-203.

112. Foster KR, Glaser R. Thermal mechanisms of interaction of radiofrequency energy with biological systems with relevance to exposure guidelines. Health Phys. 2007;92(6):609-620.

113. Fragopoulou A, Grigoriev Y, Johansson O, Margaritis LH, Morgan L, Richter E, et al. Scientific panel on electromagnetic field health risks: consensus points, recommendations, and rationales. Rev Environ Health 2010;25(4).

114. Sagar S, Struchen B, Finta V, Eeftens M, Röösli M. Use of portable exposimeters to monitor radiofrequency electromagnetic field exposure in the everyday environment. Environ Res. 2016;150:289-298.

115. Joseph W, Pareit D, Vermeeren G, Naudts D, Verloock L, Martens L, et al. Determination of the duty cycle of WLAN for realistic radio frequency electromagnetic field exposure assessment. Prog Biophys Mol Biol. 2013;111:30-36.

116. Mezei G, Benyi M, Muller A. Mobile phone ownership and use among school children in three Hungarian cities. Bioelectromagnetics 2007;28(4):309-315.

117. Böhler E, Schüz J. Cellular telephone use among primary school children in Germany. Eur J Epidemiol. 2004;19(11):1043-1050.

118. Davie R, Panting C, Charlton T. Mobile phone ownership and usage among pre-

adolescents. Telematics and Informatics. 2004;21(4):359-373.

119. Cardis E, Deltour I, Mann S, Moissonnier M, Taki M, Varsier N, Wake K, Wiart J. Distribution of RF energy emitted by mobile phones in anatomical structures of the brain. Phys. Med. Biol. 2008; 53:2771-2783.

120. Joseph W, Frei P, Röösli M, Vermeeren G, Bolte J, Thuróczy G, et al. Between-country comparison of whole-body SAR from personal exposure data in Urban areas. Bioelectromagnetics 2012;33(8):682-694.

Appendices

Appendix 1. MUHREC approval for Kindergarten RF-EMF Exposure Study

MONASH University

Monash University Human Research Ethics Committee (MUHREC)
Research Office

Human Ethics Certificate of Approval

This is to certify that the project below was considered by the Monash University Human Research Ethics Committee. The Committee was satisfied that the proposal meets the requirements of the *National Statement on Ethical Conduct in Human Research* and has granted approval.

Project Number:	**CF14/3537 - 2014001861**
Project Title:	**Assessment of radiofrequency-electromagnetic radiation exposures in preschool children in Melbourne**
Chief Investigator:	**Dr Geza Benke**
Approved:	**From: 6 January 2015 to 6 January 2020**

Terms of approval - ***Failure to comply with the terms below is in breach of your approval and the Australian Code for the Responsible Conduct of Research.***

1. The Chief investigator is responsible for ensuring that permission letters are obtained, if relevant, before any data collection can occur at the specified organisation.
2. Approval is only valid whilst you hold a position at Monash University.
3. It is the responsibility of the Chief Investigator to ensure that all investigators are aware of the terms of approval and to ensure the project is conducted as approved by MUHREC.
4. You should notify MUHREC immediately of any serious or unexpected adverse effects on participants or unforeseen events affecting the ethical acceptability of the project.
5. The Explanatory Statement must be on Monash University letterhead and the Monash University complaints clause must include your project number.
6. **Amendments to the approved project (including changes in personnel):** Require the submission of a Request for Amendment form to MUHREC and must not begin without written approval from MUHREC. Substantial variations may require a new application.
7. **Future correspondence:** Please quote the project number and project title above in any further correspondence.
8. **Annual reports:** Continued approval of this project is dependent on the submission of an Annual Report. This is determined by the date of your letter of approval.
9. **Final report:** A Final Report should be provided at the conclusion of the project. MUHREC should be notified if the project is discontinued before the expected date of completion.
10. **Monitoring:** Projects may be subject to an audit or any other form of monitoring by MUHREC at any time.
11. **Retention and storage of data:** The Chief Investigator is responsible for the storage and retention of original data pertaining to a project for a minimum period of five years.

[redacted]

Professor Nip Thomson
Chair, MUHREC

cc: Mr Chhavi Raj Bhatt; Dr Mary Redmayne; Prof Michael Abramson

Postal – Monash University, Vic 3800, Australia
Building 3E, Room 111, Clayton Campus, Wellington Road, Clayton
Telephone [redacted] Facsimile [redacted]
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ABN 12 377 614 012 CRICOS Provider #00008C

Appendix 2. Kindergarten RF-EMF Exposure Study Questionnaire

For investigator's purpose only
Preschool/kindergarten Code:
Participating child identification code:
Date and time of environmental exposure assessment:
Date and time of personal exposure assessment:
Contact person and telephone of the preschool/kindergarten:

Dear Teacher/Head Teacher and parent,

Please kindly provide us following information related to your participating preschool/kindergarten, and child and his/her home.

1. Date of birth of the participating child: ……..………
2. Gender of the child: Male ☐ Female ☐

3. Address of participating kindergarten/preschool: ………………….

4. Address of participating child's home/postal code: ………………….

5. Types and number of radiofrequency-electromagnetic radiation emitting devices or installations available in your kindergarten/preschool or home. Please tick the correct boxes and mention their numbers in the bigger boxes next to the smaller boxes given below for each radiofrequency device/installation (you can tick more than one, if applicable)

Radiofrequency devices	For school use only	For parent's use only
Wi-Fi router(s)	☐ ▭	☐ ▭
Cordless phone(s)	☐ ▭	☐ ▭
Microwave Oven(s)	☐ ▭	☐ ▭
Smart Meter(s) in or outside your building/house/flat	☐ ▭	☐ ▭
Radio/TV/base station transmitter(within 300 meters)	☐ ▭	☐ ▭

Appendix 3. Consent form for parents (Kindergarten Study)

Consent Form

We have read and reviewed your invitation letter and explanatory statement regarding our child's potential participation in your study titled '*Assessment of radiofrequency-electromagnetic radiation exposures in preschool children in Melbourne*'.

Our response to your letter (please encircle the one of the options) is as follows:

☐ We allow our child to take part in the personal exposure assessment study and the researcher at Monash University should make further contact with his/her kindergarten in regard to the study

☐ We decline to take part in the study and the researcher at Monash University should not make further contact with our child's kindergarten in regard to the study

Thank you!

Signature:

Name:

Date:

Name of the kindergarten/preschool:

Please email this signed response copy to [redacted]

Appendix 4. Consent form for principal (Kindergarten Study)

Consent Form

We have reviewed you invitation letter and explanatory statement regarding our kindergarten's potential participation in your study titled '*Assessment of radiofrequency-electromagnetic radiation exposures in preschool children in Melbourne*'.

The response of our kindergarten/preschool to your letter (please encircle the one of the options) is as follows:

☐ We would like to take part in the study and the researcher at Monash University should make further contact with our kindergarten/preschool in regard to the study

☐ We do not like to take part in the study and the researcher at Monash University should not make further contact with our kindergarten/preschool in regard to the study

Thank you!

Signature:

Name:

Date:

Name of the kindergarten/preschool:

Please email this signed response copy to [redacted]

Appendix 5. MUHREC approval for Examination of Psychological Outcomes in Students Using Radiofrequency dEvices (ExPOSURE) Study

MONASH University

Standing Committee on Ethics in Research Involving Humans (SCERH)
Research Office

Human Ethics Certificate of Approval

Date:	**2 July 2009**
Project Number:	**CF09/1210 – 2009000616**
Project Title:	**EXPOSURE – EXamination of Psychological Outcomes in Students Using Radiofrequency dEvices**
Chief Investigator:	**Prof Michael Abramson**
Approved:	**From: 2 July 2009 to 2 July 2014**

Terms of approval

1. The Chief investigator is responsible for ensuring that permission letters are obtained, if relevant, and a copy forwarded to SCERH before any data collection can occur at the specified organisation. **Failure to provide permission letters to SCERH before data collection commences is in breach of the National Statement on Ethical Conduct in Human Research and the Australian Code for the Responsible Conduct of Research**.
2. Approval is only valid whilst you hold a position at Monash University.
3. It is the responsibility of the Chief Investigator to ensure that all investigators are aware of the terms of approval and to ensure the project is conducted as approved by SCERH.
4. You should notify SCERH immediately of any serious or unexpected adverse effects on participants or unforeseen events affecting the ethical acceptability of the project.
5. The Explanatory Statement must be on Monash University letterhead and the Monash University complaints clause must contain your project number.
6. **Amendments to the approved project (including changes in personnel):** Requires the submission of a Request for Amendment form to SCERH and must not begin without written approval from SCERH. Substantial variations may require a new application.
7. **Future correspondence:** Please quote the project number and project title above in any further correspondence.
8. **Annual reports:** Continued approval of this project is dependent on the submission of an Annual Report. This is determined by the date of your letter of approval.
9. **Final report:** A Final Report should be provided at the conclusion of the project. SCERH should be notified if the project is discontinued before the expected date of completion.
10. **Monitoring:** Projects may be subject to an audit or any other form of monitoring by SCERH at any time.
11. **Retention and storage of data:** The Chief Investigator is responsible for the storage and retention of original data pertaining to a project for a minimum period of five years.

[redacted]

Professor Ben Canny
Chair, SCERH

Cc: Prof Malcolm Sim; Dr Geza Benke; Prof Rodney Croft;

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Appendix 6. ExPOSURE Study Parent's Questionnaire

MONASH University

Department of Epidemiology & Preventive Medicine
Faculty of Medicine, Nursing and Health Sciences

ATTACHMENT 5

EXPOSURE QUESTIONNAIRE: ***Part A.***

To be completed by the Parent/Guardian and returned to the school.

OFFICE USE

School code	Part ID code
visit no	
.... / .... / .... dd mm yy	

A1. Have you read and signed the consent form? Please do that before you complete this form.

☐ Yes ☐ No

A2. What is your child's date of birth? ☐☐ Day ☐☐ Month ☐☐ Year

A3. What is the sex of your child? ☐ Male ☐ Female

A4. How many older brothers and sisters does your child have? ....

A5. How many younger brothers and sisters does your child have? ....

A6. Where was your child born?

☐ Australia ☐ New Zealand ☐ UK or Ireland ☐ Italy

☐ Greece ☐ China ☐ Other

....

A7. Does your child speak any languages other than English at home? ☐ Yes ☐ No

If Yes, which language/s……………………………………………………………………..

A8. Does your child currently have any of the following medical conditions? Please only tick yes if it was diagnosed by a doctor.

a.	Asthma	☐ Yes	☐ No
b.	Diabetes	☐ Yes	☐ No
c.	Attention Deficit Hyperactivity Disorder (ADHD)	☐ Yes	☐ No
d.	Anxiety	☐ Yes	☐ No
e.	Depression	☐ Yes	☐ No
f.	Other psychiatric disorder	☐ Yes	☐ No
g.	Partial or complete blindness	☐ Yes	☐ No

A9. Does your child take regular medication?

☐ Yes ☐ No If Yes, which medication/s 1……………………………………..
2……………………………………….
3……………………………………….

A10. Has your child had a head injury where he/she lost consciousness in the past year?

☐ Yes ☐ No

If Yes, was he/she admitted to hospital? ☐ Yes ☐ No

If your child does not currently own or use a mobile phone, go now to QA21 on page 5.

The following questions relate to your child's use of mobile phones only.

A11. If **your child** currently owns or regularly use a mobile phone, what is the:

Make	Model	Service Provider
(eg Nokia)	(eg 2100)	(eg Telstra)

☐ Don't know

A12. How old was your child when he/she first started to use a mobile phone? _____ yrs old

A13. What is the average **number of calls** your child makes per week. You can give a range if that is easier. ______________ calls per week

A14. When your child **makes** a call, on average, how long is the call? __________ minutes

☐ Don't know

A15. What is the average number of calls your child **receives** on his/her mobile phone per week?

You can give a range if that is easier__________ calls per week

A16. When your child **receives** a call, on average, how long is the call? __________ minutes

☐ Don't Know

A17. How often does your child use a mobile phone **while moving in a vehicle**, such as a train, bus or car?

☐1 Never or almost never ☐2 Less than half the time ☐3 About half the time

☐4 More than half the time ☐5 Always or almost always ☐9 Don't know

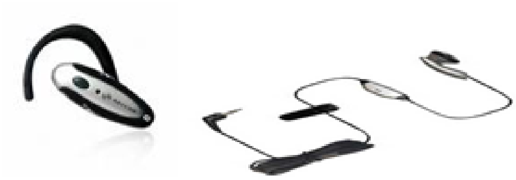
☐ 1 Hands-free set installed in a vehicle

☐ 2 A headset with a microphone (go to question B11b)

☐ 3 Both

☐ 4 Neither

☐ 9 Don't know



A18b. How often does your child use a headset with a microphone when making or receiving calls? You can give me average number of calls per week. ________calls per week.

A19. What is the average number of text (SMS) messages your child sends and receives per week? You can give a range if that is easier__________________ text messages per week.

A20. How long does your child spend using the internet on a mobile phone per week? You can give a range if that is easier __________________ minutes of internet per week.

The next three questions relate to your child's use of portable cordless phones only.

A21. Does your child use a portable cordless phone at home? ☐ Yes ☐ No (if no, go to question A24)

A22. What is the average **number** of calls your child makes and receives using the portable cordless phone per week? You can give a range if that is easier__________ calls per week.

A23. What is the average **length** of the calls your child makes and receives using the portable cordless phone per week? You can give a range if that is easier__________ minutes.

A24. How much of a health risk to you and your family are mobile phones?

☐ None ☐ Low ☐ Moderate ☐ High ☐ Don't know

Comments: Can you think of anything else about your child's family or health that might be relevant to us?

………

………

………

Thank you

Appendix 7. ExPOSURE Study Student's Questionnaire

MONASH University
Department of Epidemiology & Preventive Medicine
Faculty of Medicine, Nursing and Health Sciences

OFFICE USE

School code	Part ID code
visit no	
…….. / ……... / …….. dd mm yy	

EXPOSURE QUESTIONNAIRE: Part B.

To be completed by the Participant (Student) at the school with the assistance of the research staff.

B1. On average, how long on each **school day** do you spend doing the following activities?

	Not at all	Less than 1 Hour	About 1-2 Hours	More than 2 hours but less than 4 hours	More than 4 Hours
Watching TV/Video/DVD	□ 0	□ 1	□ 2	□ 3	□ 4
On game console	□ 0	□ 1	□ 2	□ 3	□ 4
Computer/Internet	□ 0	□ 1	□ 2	□ 3	□ 4
Listening to music	□ 0	□ 1	□ 2	□ 3	□ 4

B2. On average, how long on **weekend days** do you spend doing the following activities?

	Not at all	Less than 1 Hour	About 1-2 Hours	More than 2 Hours but less than 4 Hours	More than 4 Hours
Watching TV/Video	□ 0	□ 1	□ 2	□ 3	□ 4
On game console	□ 0	□ 1	□ 2	□ 3	□ 4
Computer/Internet	□ 0	□ 1	□ 2	□ 3	□ 4
Listening to music	□ 0	□ 1	□ 2	□ 3	□ 4

B3a. Have you ever used mobile phones to make or receive calls? □ Yes □ No

B3b. Do you currently <u>own</u> a mobile phone? □ Yes □ No

B3c. Do you currently <u>use</u> a mobile phone? □ Yes □ No

If you do <u>not</u> currently own or use a mobile phone, go to Question B5.

B4. When you use a mobile phone, do you generally use it on the right or left side of your head? (by generally we mean more than 50% of the time):

☐ 1. Right side ☐ 2. Left side ☐ 3. Both/either ☐ 9. Don't remember

B5. Are you mainly right or left handed?

☐ 1. Right handed ☐ 2. Left handed ☐ 3. No preference ☐ 9. Don't know

The last four questions ask about your life in general.

B6. During the past week, how many times did you exercise, such as jogging, walking, karate, dancing, skipping?

☐ not at all ☐ 1 or 2 times ☐ 3 or 4 times ☐ 5 or more times

B7. During the past week, how many times did you play active sport, such as cricket, softball, tennis, basketball, swimming or football?

☐ not at all ☐ 1 or 2 times ☐ 3 or 4 times ☐ 5 or more times

B8. During the past week, how many times outside school hours, did you just hang out with friends?

☐ not at all ☐ 1 or 2 times ☐ 3 or 4 times ☐ 5 or more

B9. During the past week, how many times did you watch television or videos or play video games?

☐ not at all ☐ 1 or 2 times ☐ 3 or 4 times ☐ 5 to 9 times ☐ 10 or more times

Thank You.

Appendix 8. Consent form for principal (ExPOSURE Study)

MONASH University

Department of Epidemiology & Preventive Medicine
Faculty of Medicine, Nursing and Health Sciences

ATTACHMENT 7

CONSENT FORM: PRINCIPAL OF THE PARTICIPATING SCHOOL

Name of Principal: ……………………………………………………………………….

School Address: ……………………………………………………………………….

……………………………………………………….. **P/code** ………

Project Title:	EXPOSURE - EXamination of Psychological Outcomes in Students Using Radiofrequency dEvices
Name(s) of Investigators:	Professor Michael Abramson Professor Malcolm Sim Dr Geza Benke Professor Rodney Croft

1. I have received an Information Sheet explaining this project to me.
2. I agree that I participate in this project, the particulars of which, including details of the interviews and questionnaires – have been explained to me.
3. I agree to participating students bringing their mobile phones to school for the purpose of this study.
4. I acknowledge that:
   (a) Having read the Information Sheet I agree to the general purpose, methods and demands of the study.
   (b) I have been informed that I am free to withdraw from the project at any time and to withdraw any unprocessed data previously supplied.
   (c) The project is for the purpose of research. It may not be of direct benefit to me.
   (d) The confidentiality of the information provided will be safeguarded.
   (e) The security of the research data is assured during and after completion of the study. The data collected during the study may be published, and a report of the project outcomes will be provided to the school. Any information that will identify me will not be used.

Principal Consent

I consent that my school can participate in the above project.

Signature: Name: ……………………………………………… Date: ……………………

Signature……………………………………………………………………………………….

Principals will receive a photocopy of this consent form after it has been signed.

Appendix 9. Consent form for class teacher (ExPOSURE Study)

MONASH University
Department of Epidemiology & Preventive Medicine
Faculty of Medicine, Nursing and Health Sciences

CONSENT FORM: TEACHER OF THE PARTICIPATING CLASS

Name of Class Teacher: ……………………………………………………………………….

School Address: ……………………………………………………………………….

……………………………………………………….. **P/code** ………

Project Title: EXPOSURE - EXamination of Psychological Outcomes in Students Using Radiofrequency dEvices

Name(s) of Investigators: Professor Michael Abramson
Professor Malcolm Sim
Dr Geza Benke
Professor Rodney Croft

1. I have received an Information Sheet explaining this project to me.
2. I agree that I participate in this project, the particulars of which, including details of the interviews and questionnaires – have been explained to me.
3. I agree to participating students bringing their mobile phones to school for the purpose of this study.
4. I acknowledge that:
   (a) Having read the Information Sheet, I agree to the general purpose, methods and demands of the study.
   (b) I have been informed that I am free to withdraw from the project at any time and to withdraw any unprocessed data previously supplied.
   (c) The project is for the purpose of research. It may not be of direct benefit to me.
   (d) The confidentiality of the information provided will be safeguarded.
   (e) The security of the research data is assured during and after completion of the study. The data collected during the study may be published, and a report of the project outcomes will be provided to the school. Any information that will identify me will not be used.

Teacher Consent

I consent that I participate in the above project.

Signature: Name: ……………………………………………… Date: ……………………

Signature……………………………………………………………………………………

Teachers will receive a photocopy of this consent form after it has been signed.

Department of Epidemiology and Preventive Medicine (MonCoEH)
Monash University, The Alfred Hospital, Commercial Road, Melbourne 3004
T [redacted] www.monash.edu.au/epidemiology

Appendix 10. Consent form for parents/guardians (ExPOSURE Study)

MONASH University

University of Wollongong

<<Parent name>>
<<Street>>
<<Suburb>><<State>><<Postcode>>

<<Date>>

Dear <<*Parent name*>>,

Your child is one of a number of Grade 5 students at <<*School name*>> who participated in the EXPOSURE Study follow-up on the <<*date of testing*>>.

As the part of the study we require parents to complete a consent form and short questionnaire for our records. Unfortunately we were unable to locate your consent form and questionnaire. It is important for the purpose of the study that we have a record of your consent and also collect the information in the parent questionnaire.

Please complete the parent/guardian consent form ***and*** parent questionnaire and return these in the enclosed reply paid envelope along with your child's consent form. Also enclosed is the schools information sheet that provides an overview of the study for your own record.

Should you have any questions about this, please contact Anna Dalecki on [redacted]

Yours Sincerely,

Prof Rodney Croft
Department of Psychology
University of Wollongong

Department of Psychology
University of Wollongong
Northfields Avenue, Wollongong 2522
[redacted]

Department of Epidemiology & Preventive Medicine
Faculty of Medicine, Nursing and Health Sciences

Participant ID number ………………

CONSENT FORM FOR CHILDREN

Name: …………………………………………………………………………….

Address: …………………………………………………………………………….

……………………………………………………….**P/code** …………

Project Title: EXPOSURE - EXamination of Psychological Outcomes in Students Using Radiofrequency dEvices

Name(s) of Investigators: Professor Michael Abramson
Professor Malcolm Sim
Dr Geza Benke
Professor Rodney Croft

1. I have received an Information Sheet explaining this project to me.
2. I agree to participate in this project, the questionnaires and tests have been explained to me.
3. I acknowledge that:
   (a) After reading the Information Sheet, I agree to the general purpose, methods and demands of the study.
   (b) I have been informed that I am free to withdraw from the project at any time and to withdraw any data previously supplied.
   (c) The project is for the purpose of research. It may not directly help me.
   (d) The information provided will be kept confidential.
   (e) The results will be kept secure. The data collected during the study may be published, and a report of the project outcomes will be provided to the school. I will not be named.

Participant Consent

I agree to participate in this project.

Signature: Name: ……………………………………………… Date: ……………………

Signature……………………………………...

Department of Psychology
University of Wollongong
Northfields Avenue, Wollongong 2522
Telephone +61 2 4221 3742; Facsimile +61 2 4221 4163

Appendix 11. Acceptance letter from Environmental Health

Date: 12 Apr 2017

To: "Chhavi R. Bhatt" [redacted] From:"Environmental Health Editorial Office" [redacted]

Subject: Decision has been reached on your submission to Environmental Health - ENHE-D-17-00044R1

Use of mobile and cordless phones and change in cognitive function: a prospective cohort analysis of Australian primary school children

Chhavi R. Bhatt, MSc; Geza Benke, PhD; Catherine L. Smith, MSc, MPH; Mary Redmayne, PhD; Christina Dimitriadis, BA; Anna Dalecki, PhD; Skye Macleod, PhD; Malcolm R. Sim, MBBS, PhD; Rodney J. Croft, PhD; Rory Wolfe, PhD; Jordy Kaufman, PhD; Michael J. Abramson, MBBS, PhD

Environmental Health

Dear Mr Bhatt,

I am pleased to inform you that your manuscript "Use of mobile and cordless phones and change in cognitive function: a prospective cohort analysis of Australian primary school children" (ENHE-D-17-00044R1) has been accepted for publication in Environmental Health.

Before publication, our production team will check the format of your manuscript to ensure that it conforms to the standards of the journal. They will be in touch shortly to request any necessary changes, or to confirm that none are needed.

Any final comments from our reviewers or editors can be found, below. Please quote your manuscript number, ENHE-D-17-00044R1, when inquiring about this submission.

We look forward to publishing your manuscript and I do hope you will consider Environmental Health again in the future.

Best wishes,

David Ozonoff, MD, MPH

Environmental Health

Appendix 12. An end piece to chapter 6 (a published paper)

This refers to my response to two queries of one of the examiners

Query 1: Bias – it is correct (page 108 bottom of the page) that there is likely to be misclassification of exposure, and this can lead to bias. What kind of bias? In what direction might the measure of effect be shifted?

Response:

In the context of my study on the children's use of MP/CP and their cognitive effects, RF-EMF exposure measure was self-reported weekly number of calls on MP/CP (reported by a parent of each participant) categorised into increase or decrease/no change in MP/CP calls. Any deviation of the change in phone use would result in exposure misclassification, non-differential or differential (1)**.** Non-differential misclassification biases the estimated effect towards the null. On the other hand, differential misclassification of the exposure could bias the estimated effect away from null in either direction.

Query 2: Further follow-up – "may be more sensitive". Why? Are there likely to be lagged effects? Or an accumulation of small effects? Or is it just a matter of increasing the number of observations and reducing sampling error?

Response: If longer follow-up times (> 1 year) were available; firstly, children's phone use pattern could have changed (most likely to increase); secondly, their cognition would have changed as a natural mental development process irrespective of any influence of phone usage. In addition, cognition could have also been changed if their phone usage had any effect on it. Therefore, lagged effects due to the longer follow-up period would have provided better estimates of the effects of MP/CP use in any potential change in cognition (2).

References

1. Röösli M, Vienneau D. Epidemiology of electromagnetic fields. In: Röösli M (ed). Epidemiological exposure assessment. CRC Press Taylor & Francis Company, 2014, pp 35–55.
2. Todd PE, Wolpin KI. The Production of Cognitive Achievement in Children: Home, School and Racial Test Score Gaps. *Journal of Human Capital* 2007, 1: 91-136.