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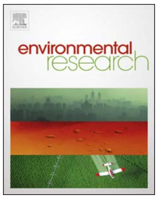

Representativeness and repeatability of microenvironmental personal and head exposures to radio-frequency electromagnetic fields

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ABSTRACT

The aims of this study were to: i) investigate the repeatability and representativeness of personal radio frequency-electromagnetic fields (RF-EMFs) exposure measurements, across different microenvironments, ii) perform simultaneous evaluations of personal RF-EMF exposures for the whole body and the head, iii) validate the data obtained with a head-worn personal distributed exposimeter (PDE) against those obtained with an on-body worn personal exposimeter (PEM). Data on personal and head RF-EMF exposures were collected by performing measurements across 15 microenvironments in Melbourne, Australia. A body-worn PEM and a head-worn PDE were used for measuring body and head exposures, respectively. The summary statistics obtained for total RF-EMF exposure showed a high representativeness ($r^2 > 0.66$ for two paths in the same area) and a high repeatability over time ($r^2 > 0.87$ for repetitions of the same path). The median head exposure in the 900 MHz downlink band ranged between 0.06 V/m and 0.31 V/m. The results obtained during simultaneous measurements using the two devices showed high correlations ($0.42 < r^2 < 0.94$). The highest mean total RF-EMF exposure was measured in Melbourne's central business district (0.89 V/m), whereas the lowest mean total exposure was measured in a suburban residential area (0.05 V/m). This study shows that personal RF-EMF microenvironmental measurements in multiple microenvironments have high representativeness and repeatability over time. The personal RF-EMF exposure levels (i.e. body and head exposures) demonstrated moderate to high correlations.

1. Introduction

Radiofrequency-electromagnetic fields (RF-EMFs) are omnipresent in our environment, as they enable wireless telecommunication. Consequently, most humans are constantly exposed to RF-EMFs and technologies that emit RF-EMFs such as mobile phones or mobile phone base stations. These RF-EMFs can have thermal effects (ICNIRP, 1998).

Personal exposure to RF-EMFs can be measured using wearable devices, so-called personal exposimeters (PEMs) (Joseph et al., 2010; Bolte et al., 2016), which can register RF-EMFs over a wide range of frequencies (0.1 – 6 GHz). These devices have previously been used systematically to investigate personal exposure in different microenvironments. A microenvironmental exposure assessment study usually consists of the following steps: Firstly, a set of predefined geographical areas is defined in which measurements will take place. Secondly, one path through the area is then commonly defined, and a trained researcher, wearing the PEM, follows those predefined paths for a number of times to evaluate personal exposure in that particular area/path (Bhatt et al., 2016a; Sagar et al., 2016; Urbinello et al., 2014a). This approach has the advantage that the researcher can control and preferentially eliminate self-induced RF-EMF exposure (exposure caused by the researcher's RF-EMF emitting devices), which causes measurement uncertainties (Röösli et al., 2010), and reduces interpersonal variability of the measurements (Neubauer et al., 2010).

There are four challenges associated with microenvironmental personal exposure measurements of RF-EMFs. Firstly, it is unclear whether repeated microenvironmental measurements of RF-EMFs yield reproducible results. Secondly, the representativeness of selected paths for the microenvironments in which they are defined has not been conclusively demonstrated. Previous findings (Beekhuizen et al., 2013;

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Sagar et al., 2016; Urbinello et al., 2014a) suggest that a path that requires at least 15 min of transportation time yields a reproducible arithmetic mean exposure measure. However, measured RF-EMF data can show a highly non-Gaussian distribution (Bhatt et al., 2016b), which implies that small (logarithmic) changes in the data could have a large effect on the arithmetic mean. Thirdly, there have been almost no studies that validate PEM measurements. Beekhuizen et al. (2013) used numerical simulations to compare PEM measurements and simulated RF-EMF fields. Thielens et al. (2016) used static measurements with a spectrum analyser and tri-axial antenna to compare with PEM measurements. However, both studies could not take temporal profiles of exposure into account. A successful approach for internal validation was used in Bhatt et al. (2016a), where two different types of PEMs were used simultaneously during the same microenvironmental measurements. Fourthly, measurements using PEMs are still confronted with relatively large measurement uncertainties up to a factor of one thousand (Bolte et al., 2016; Iskra et al., 2011). These are mainly caused by shielding of the body and detuning of the measurement device in the presence of the body (Bolte, 2016; Gajšek et al., 2015; Iskra et al., 2011; Neubauer et al., 2010; Thielens et al., 2015). The measurement uncertainties could be reduced by using an on-body calibration of the PEMs (Bolte, 2016; Bhatt et al., 2016b) and averaging over multiple devices on the body (Thielens et al., 2016). This led to the development of a personal distributed exposimeter (PDE) (Thielens et al., 2013), in the Global System for Mobile communications (GSM) 900 MHz downlink (DL) band. This frequency band was chosen for prototyping, since it is one of the highest contributors to total DL exposure from mobile phone base stations (Bhatt et al., 2016a, 2016b; Sagar et al., 2016).

Recently, considerable research attention has been focused on potential cognitive effects of RF-EMF exposure (Abramson et al., 2009; Kheifets et al., 2005; Roser et al., 2016; Bhatt et al., 2017), in particular associated with RF-EMF exposures to the head. In order to investigate such effects, there is a need to improve the assessment of head-specific personal exposure levels (van Deventer et al., 2011), both from near-field RF-EMF devices such as mobile phones and far-field RF-EMF devices such as mobile phone base stations. In order to measure RF-EMF exposure to the head, we have installed the PDE into a helmet, so that it can measure head-specific RF-EMF exposure in the 900 DL band.

The goals of this study were to: i) perform (for the first time) simultaneous evaluation of the whole body (with PEMs) and the head (PDE-Helmet) RF-EMF exposures across various microenvironments, ii) evaluate representativeness and repeatability of personal microenvironmental RF-EMF exposure measurements, and iii) correlate and validate the concurrently measured RF-EMF exposures to the body and the head.

2. Materials and methods

2.1. Study areas and design

The study was conducted between 15th November and 22nd December 2016 in greater Melbourne, Australia, where 15 microenvironments (Röösli et al., 2010; Urbinello et al., 2014a, 2014b; Bhatt et al., 2016a) were defined. The characteristics of each microenvironment, its spatial characteristics, and the activities undertaken therein by the subjects (researchers AT, CB and CRB) while performing personal body and head exposure measurements are summarized in Table A1 in Appendix A.

The studied microenvironments (see Table A1 in Appendix A) have been selected to cover different (sub-)urban activities in the greater Melbourne area: residential areas (9, 11 – 15), industrial areas (area 7), areas dedicated to trade, commerce and tourism (3, 5, and 6), recreational areas (areas 1–3, and 8), and college/university areas (4 and 10). Another aim was to cover different population densities in the greater Melbourne area. The studied microenvironments covered population densities from 250 inhabitants/km^2 up to 15,000 inhabitants/km^2. This resulted in a total of 15 studied microenvironments.

In each microenvironment, two paths of similar length (max ± 20% deviation) were predefined. In every microenvironment, one out of three different modes of transportation was used to follow the paths: walking, driving a car, and riding a bicycle. The paths were defined in such a way that it took at least 15 min to follow them, in line with the recommendations of Beekhuizen et al. (2013), Sagar et al. (2016), and Urbinello et al. (2014a). These paths were followed at three different timeslots during the day: morning (9 a.m. – 12noon), midday (12noon – 3 p.m.), and afternoon (3 p.m. – 6 p.m.). Measurements were only conducted on weekdays - from Monday to Friday. Each path was repeated five times, once on each day of the week, and was executed twice in two different timeslots and once in the remaining third timeslot. Of the five repetitions, two were executed in such a way that two researchers followed the two paths in the same microenvironment simultaneously. This resulted in $15 \times 2 \times 5 = 150$ measurements along predefined paths. In addition to these microenvironmental measurements, measurements were also conducted in seven places of interest, which were six train and subway stations and in the outskirts of one public playground. Measurements were also performed during transportation between the different paths. During these measurements, the following modes of transportation were used: car, bike, train, tram, metro and walking (see Appendix A). The difference between the 15 studied microenvironments and the places of interest was that the researchers had to follow predefined paths only in the microenvironments, while they were free to move around in the places of interest. The type and route of transportation in between the microenvironments was also not predefined.

Two types of measurements were conducted: Firstly, one researcher followed one of the predefined paths while wearing two PEMs and the PDE-Helmet if the researcher was riding a bike (areas 1, 2 and 9). Secondly, two researchers followed the two paths in one area simultaneously, each wearing one PEM. One of the researchers wore the PDE-Helmet if the paths were followed while riding a bicycle.

During the measurements, GPS coordinates were collected by two PEMs that were worn on the body of the researcher(s). The researchers' wireless devices such as mobile phones were in flight mode, eliminating any contribution to RF-EMF exposure.

2.2. Measurement devices

2.2.1. The ExpoM-RF

The ExpoM-RF is a PEM developed by Fields At Work (http://www.fieldsatwork.ch), which measures electric field strengths on the body (E_{body}) in 16 different frequency bands every 4 s Fig. 1(a) shows an illustration of the ExpoM-RF. Table I lists the frequency bands and the detection ranges of the Expom-RF in those bands. The ExpoM-RF was not calibrated on the body of the subject in this study, since we were interested in comparing our results to other studies where such a calibration was not usually conducted.

2.2.2. The PDE-Helmet

The PDE-Helmet is a measurement device developed at Ghent University (Thielens et al., 2016). It uses multiple RF nodes that are distributed over the head, in order to reduce the measurement uncertainty on the incident RF power density. The device measures incident electric fields on the head of a subject (E_{head}) with a frequency of