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Review Article

Lessons learnt on biases and uncertainties in personal exposure measurement surveys of radiofrequency electromagnetic fields with exposimeters

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ABSTRACT

Personal exposure measurements of radio frequency electromagnetic fields are important for epidemiological studies and developing prediction models. Minimizing biases and uncertainties and handling spatial and temporal variability are important aspects of these measurements. This paper reviews the lessons learnt from testing the different types of exposimeters and from personal exposure measurement surveys performed between 2005 and 2015. Applying them will improve the comparability and ranking of exposure levels for different microenvironments, activities or (groups of) people, such that epidemiological studies are better capable of finding potential weak correlations with health effects.

Over 20 papers have been published on how to prevent biases and minimize uncertainties due to: mechanical errors; design of hardware and software filters; anisotropy; and influence of the body. A number of biases can be corrected for by determining multiplicative correction factors. In addition a good protocol on how to wear the exposimeter, a sufficiently small sampling interval and sufficiently long measurement duration will minimize biases. Corrections to biases are possible for: non-detects through detection limit, erroneous manufacturer calibration and temporal drift. Corrections not deemed necessary, because no significant biases have been observed, are: linearity in response and resolution. Corrections difficult to perform after measurements are for: modulation/duty cycle sensitivity; out of band response aka cross talk; temperature and humidity sensitivity. Corrections not possible to perform after measurements are for: multiple signals detection in one band; flatness of response within a frequency band; anisotropy to waves of different elevation angle.

An analysis of 20 microenvironmental surveys showed that early studies using exposimeters with logarithmic detectors, overestimated exposure to signals with bursts, such as in uplink signals from mobile phones and WiFi appliances. Further, the possible corrections for biases have not been fully applied. The main findings are that if the biases are not corrected for, the actual exposure will on average be underestimated.

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1. Introduction

To investigate whether an association exists between exposure to ambient radiofrequency (RF) electromagnetic fields (EMF) from broadcasting transmitters and wireless devices and adverse health effects, epidemiological studies have been conducted in several, mostly European, countries (Gajsek et al., 2013). They have employed several methods with different levels of accuracy to determine or estimate the individual exposure. As only a small proportion of the population is highly exposed, one should make sure that those who are considered as exposed, are in fact exposed. Therefore, a method for exposure classification should display a high specificity, i.e. the number of false positives should be kept at a minimum (Neubauer et al., 2007). Even a specificity slightly lower than '1' (one) will decrease the estimate of a potential true relative risk considerably. Therefore, in epidemiological studies determining the exposure accurately, or at least the ranking of exposure in groups, is necessary. Also in dosimetric studies, the actual field inside the body can only be derived from an accurately measured field outside the body (Bahillo et al., 2008; Joseph et al., 2008; Vermeeren et al., 2008, 2013a; Iskra et al., 2010; Neubauer et al., 2010; Lauer et al., 2013). Personal exposure measurements provide the best means to observe the exposure of people during the entire day without having to assume proxies, provided the measurement uncertainties can be kept as small as possible (Bolte et al., 2011; Lauer et al., 2012; Radon et al., 2006). The major drawback though, is that using them is time and budget consuming. Other methods such as self-reported exposure or geocoded distance are poor surrogates for personal exposure, while spot measurements and modelling exposure from fixed site transmitters are conceivable surrogates for personal exposure, particularly for residential exposure (Frei et al., 2010). New developments are the extensive modelling techniques for propagation from source to homes or inside homes (Neitzke et al., 2007; Bürgi et al., 2008, 2010; Beekhuizen et al., 2013, 2014), that can be combined with microenvironmental exposure characterisation and the time spent by an individual in these microenvironments to develop personal exposure prediction models (Frei et al., 2009b; Roser et al., 2015). The advantage of models based on personal exposure measurements in microenvironments is that they will give a less time and budget consuming exposure estimate of large groups of people. The large within variability for microenvironments or activities is a challenge in constructing such exposure prediction models.

Personal exposure meters, or exposimeters, measuring everyday exposure levels to RF EMF have been employed in research since 2005. They are portable devices that commonly measure narrowband exposure from specific sources: FM radio, TV, base stations (downlink) and mobile phones (uplink), cordless phones, and wireless internet. Before 2005 also exposimeters for occupational exposure to RF EMF had been employed, though they tended to warn workers for exceedance of the ICNIRP limits (ICNIRP, 1998) or a preset value by an alarm and most of them did not log the measurements (Mann, 2010). The ability of the body-worn exposimeters to accurately measure and log the ambient RF EMF has been discussed by various research groups. In broad terms, these either measure the response of the exposimeter to a standard input signal (Bolte et al., 2011; Bornkessel et al., 2010; Knafl et al., 2008; Lauer et al., 2012; Lehmann et al., 2006; Mann et al., 2005; Nájera-López et al., 2015; Radon et al., 2006; Thielens et al., 2013, 2015a,b,c,d) or model the influence of the body (Bahillo et al., 2008; Blas et al., 2007; De Miguel-Bilbao et al., 2015; Gryz et al., 2015; Iskra et al., 2007, 2010, 2011; Joseph et al., 2008; Neubauer et al., 2008, 2010; Vermeeren et al., 2008, 2010, 2013a; Roderíguez et al., 2011).

Further, in population (Heinrich et al., 2010, 2011; Kühnlein et al., 2009; Radon et al., 2006; Thomas et al., 2008a,b, 2010), microenvironmental (Bolte and Eikelboom, 2012; Frei et al., 2009a,b; Joseph et al., 2008, 2010, 2012; Juhász et al., 2011; Markakis and Samaras, 2013; Roser et al., 2015; Thuróczy et al., 2008; Trcek et al., 2007; Urbinello et al., 2014a,c; Vermeeren et al., 2013b; Valič et al., 2009, 2014; Viel et al., 2009a) and temporal (Urbinello et al., 2014b; Viel et al., 2011) surveys the spatial and temporal variability and the reproducibility of measurements by the same volunteers during their daily activities has been discussed. A population survey studies (the differences between) the exposure of individuals, so the group of participants should be a randomly selected representative sample of the population under study. A microenvironmental survey looks at (the differences between) exposure during typical behaviour in relevant microenvironments. So not a random sample is required, but rather a group of participants representing the whole range of exposure relevant behaviours and activities in the environments of interest. In microenvironmental studies also commissioned workers doing repeated measurements in a type of microenvironment can be hired. Temporal studies are generally performed by measuring along the same itinerary at the same time over a period of several months or years. In all of these kinds of surveys the temporal and spatial variability and the reproducibility of measurements should be assessed, in order to make any general remarks on the exposure situations and whether the exposure characterisation of a person or microenvironment and the exposure prediction based on that is an accurate description of real life situations.

The narrow band exposimeters that have been used in most measurement surveys are the ESM 140 (Maschek, Kaufering, Germany; www.maschek.de), EME Spy types 90, 120, 121, 140, 200 (Satimo, Cortaboeuf, France, http://www.satimo.fr), and ExpoM (Fields at Work, Zürich, Switzerland, http://www.fieldsatwork.ch). Also Ghent University in Belgium has been developing a personal distributed exposimeter (PDE) with textile antennas that can be sown in garments (Thielens et al., 2013). Note that these exposimeters are designed for measuring exposure of members of the general public during everyday activities. They are not covering the range, nor the exposure strength, that may occur in occupational settings such as antenna workers may encounter. Mostly used in population surveys is the ESM 140, in large microenvironmental measurement surveys the EME Spy 120 and 121, and in temporal surveys the EME Spy 140. In validation studies for development of environmental or personal prediction models, also the EME Spy 140 has often been used. The EME Spy 200 and ExpoM have been used, but we only found one journal paper reporting on their use yet (Roser et al., 2015). They all differ in size, weight, number of frequency bands associated with a source, measurement interval, internal memory capacity, lower and upper detection limit, and availability of built-in GPS-logger. Most important of all, as they all have different hardware designs such as internal antenna configuration and logarithmic or RMS detector, their sensitivities differ, and therefore their biases and measurement uncertainties.

Major limitations for all narrowband exposimeters are that: they cannot measure the entire electromagnetic spectrum; they are not suitable for measuring the near-field of sources; they measure only local exposure of the body; and they cannot be worn at all times, f.i. during wet or sports activities or while sleeping. Not being able to measure exposure from devices used close to the body is a key deficiency as these devices significantly contribute to the total exposure, defined as summed power density over all measured frequency bands, for instance the use of one's own cell phone is a large contributor that cannot be properly measured by an exposimeter (Dürrenberger et al., 2014).

Not being able to measure the entire electromagnetic spectrum, but only between 12 and 20 frequency bands typically used by broadcast and telecommunication sources, leads to an incomplete assessment of the total exposure. For instance AM transmitters, Bluetooth, 400 MHz babyphones, 27 MHz and other HAM radio transmitters are not being measured by any of the exposimeters, thus leading to an exposure bias and possible misclassification regarding total exposure to radiofrequency electromagnetic fields.

To be able to compare or combine personal measurements, even from different units of the same type, systematic biases should be corrected for, often by multiplicative correction factors, and measurement uncertainties should be kept to a minimum. As with time due to

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