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A Source-based Measurement Database for Occupational Exposure Assessment of Electromagnetic Fields in the INTEROCC Study: A Literature Review Approach

Javier Vila[1,2,3*], Joseph D. Bowman[4], Lesley Richardson[5], Laurel Kincl[6], Dave L. Conover[†], Dave McLean[7], Simon Mann[8], Paolo Vecchia[9], Martie van Tongeren[10] and Elisabeth Cardis[1,2,3], on behalf of the INTEROCC Study Group[‡]

1.Center for Research in Environmental Epidemiology (CREAL), Barcelona, Spain;
2.Universitat Pompeu Fabra (UPF), Barcelona, Spain;
3.CIBER Epidemiología y Salud Pública (CIBERESP), Barcelona, Spain;
4.National Institute for Occupational Safety and Health (NIOSH), Cincinnati, OH, USA;
5.University of Montreal Hospital Research Centre (CRCHUM), Montreal, Canada;
6.Oregon State University (OSU), Corvallis, OR, USA;
7.Massey University, Wellington, New Zealand;
8.Public Health England (PHE), Chilton, UK;
9.National Institute of Health (ISS), Rome, Italy;
10.Institute of Occupational Medicine (IOM), Edinburgh, UK
*Author to whom correspondence should be addressed. Tel. +34-932-147-325; fax: +34-932-147-302; e-mail: jvila@creal.cat
†Deceased, formerly NIOSH, Cincinnati, OH, USA
‡INTEROCC Study Group members: International Coordination - Elisabeth Cardis (CREAL), Laurel Kincl (now at Oregon State University), Lesley Richardson (now at University of Montreal Hospital Research Centre); Canada - Jérôme Lavoué and Jack Siemiatycki (University of Montreal Hospital Research Centre), Daniel Krewski (University of Ottawa); Australia - Geza Benke (Monash University); France - Marie-Elise Parent (INRS-Institut Armand-Frappier); France - Martine Hours (IFSTTAR); Germany - Brigitte Schlehofer and Klaus Schlaefer (DKFZ); Joachim Schüz (now at IARC), Maria Blettner (Universitätsmedizin Mainz); Israel - Siegal Sadetzki (Gertner Institute, Chaim Sheba Medical Center and Tel Aviv University); New Zealand - Dave McLean (Massey University); UK - Sarah Fleming (University of Leeds), Martie van Tongeren (Institute of Occupational Medicine - IOM); USA - Joseph D Bowman (NIOSH).
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ABSTRACT

Introduction: To date, occupational exposure assessment of electromagnetic fields (EMF) has relied on occupation-based measurements and exposure estimates. However, misclassification due to between-worker variability remains an unsolved challenge. A source-based approach, supported by detailed subject data on determinants of exposure, may allow for a more individualized exposure assessment. Detailed information on the use of occupational sources of exposure to EMF was collected as part of the INTERPHONE-INTEROCC study. To support a source-based exposure assessment effort within this study, this work aimed to construct a measurement database for the

occupational sources of EMF exposure identified, assembling available measurements from the scientific literature.
Methods: First, a comprehensive literature search was performed for published and unpublished documents containing exposure measurements for the EMF sources identified, ***a priori*** as well as from answers of study subjects. Then, the measurements identified were assessed for quality and relevance to the study objectives. Finally, the measurements selected and complementary information were compiled into an Occupational Exposure Measurement Database (OEMD).
Results: Currently, the OEMD contains 1624 sets of measurements (>3000 entries) for 285 sources of EMF exposure, organized by frequency band (0 Hz to 300 GHz) and dosimetry type. Ninety-five documents were selected from the literature (almost 35% of them are unpublished technical reports), containing measurements which were considered informative and valid for our purpose. Measurement data and complementary information collected from these documents came from 16 different countries and cover the time period between 1974 and 2013.
Conclusion: We have constructed a database with measurements and complementary information for the most common sources of exposure to EMF in the workplace, based on the responses to the INTERPHONE-INTEROCC study questionnaire. This database covers the entire EMF frequency range and represents the most comprehensive resource of information on occupational EMF exposure. It is available at www.crealradiation.com/index.php/en/databases.

KEYWORDS: electromagnetic fields; EMF sources; exposure database; literature review

INTRODUCTION

Occupational exposure to electric, magnetic, and electromagnetic fields (EMF) occurs wherever electricity is generated, distributed, or used in the work environment, and when EMF are used as part of the operating mechanism (e.g. radio broadcasting). EMF can be characterized by their frequency (in hertz or cycles/second) and the magnitudes of the electric and magnetic field vectors. The frequency determines the biophysical mechanism of interaction and, therefore, the biological effects of EMF, while the field magnitude influences the strength of the potential biological response (Röösli, 2014). Frequencies can range from static magnetic fields (SMF), which do not vary with time (0 Hz), to radiofrequency (RF) fields (up to 300 GHz) that oscillate over a million times a second (see Table 1).

Table 1. EMF frequency bands used in INTEROCC

Frequency band labels[a]	ITU[b] frequency bands	Frequency range
SMF	SMF	0–0 Hz
ELF	ELF	3–3000 Hz
IF	VLF-LF	3–300 kHz
IF	MF-HF	300 kHz–10 MHz
RF	HF-VHF	10–300 MHz
RF	UHF-MW	300 MHz–300 GHz

[a]SMF, static magnetic fields; ELF, extremely low-frequency; IF, intermediate; RF, radiofrequency; VLF-LF, very low frequency-low frequency; MF-HF, medium frequency-high frequency; HF-VHF, high frequency-very high frequency; UHF-MW, ultra high frequency-micro waves.
[b]International Telecommunications Union (ITU, 2008).

Numerous technologies in the workplace are responsible for EMF emissions and the number and diversity of EMF sources has increased enormously in the last century (Hitchcock and Patterson, 1995). SMF are emitted by medical, transportation, and other machinery based on direct current electricity or permanent metal magnets. Extremely low-frequency (ELF) fields are associated with the generation and distribution of alternating current electricity, and use of domestic/office appliances and industrial/commercial equipment. In the International System of Units (SI), both SMF and ELF magnetic fields (B-fields) are measured in micro-Tesla [μT], although the obsolete milli-Gauss units (1 mG = 0.1 μT) are found in the older scientific literature and contemporary media. RF fields are associated with object-detection systems, telecommunications, and some heating-based manufacturing and medical equipment. Some newer technologies, such as object identification and induction heating, emit intermediate frequency (IF) fields. IF and RF magnetic fields (H-fields) are measured in amperes per metre [A m^{-1}] and electric fields (E-fields) in volts per metre [V m^{-1}]. For high frequencies, the magnitude of the electric field, or power density (PD), is often measured in watts per square metre [W m^{-2}], although the units of milli-watts per square centimetre [1 mW cm^{-2} = 0.1 W m^{-2}] can also be found.

The possibility that EMF exposure is associated with chronic health problems has been postulated by numerous investigators. The most consistent evidence today is for an association between ELF and childhood leukaemia risk (Sienkiewicz *et al.*, 2012). Several studies (INTERPHONE Study Group, 2010; Baan *et al.*, 2011; Cardis *et al.*, 2011) also suggest a possible association between RF exposure and brain and central nervous system tumours risk. Based on existing scientific evidence, the International Agency for Research on Cancer (IARC) classified both ELF (magnetic fields) and RF as group 2B, possibly carcinogenic to humans (IARC, 2002, 2013). The evidence for occupational EMF exposure has been judged inadequate, however, due to exposure assessment limitations and small sample sizes. Recent findings using larger number of cases (Turner *et al.*, 2014) suggest that glioma risk may be associated with recent (<5 years) ELF magnetic field occupational exposures. These results, coupled with uncertain effects of EMF on acute health conditions and reproductive and neurodegenerative outcomes (Röösli, 2014) and lack of information about possible health risks from IF field exposures (Sienkiewicz *et al.*, 2012), highlight the need for further and improved studies, including better exposure assessment methods.

A multi-national case-control study of central nervous system tumour risk in relation to RF exposure from mobile telephones, INTERPHONE (Cardis *et al.*, 2007), was conducted in 13 countries, including over 6000 cases and 7000 controls recruited between 2000 and 2005. The questionnaire used provided detailed information not only on historical mobile phone use and relevant potential confounders, such as smoking, socioeconomic status, ionizing radiation or allergies, but also on the subjects' occupational histories and work with EMF sources. The availability of this information provides a unique opportunity to assess tumour risk in relation to occupational EMF exposure in a large population.

The INTEROCC project, involving seven INTERPHONE countries (Australia, Canada, France, Germany, Israel, New Zealand, and the UK), was set up to make use of this valuable data set. The main aim of INTEROCC is to assess occupational EMF and chemical exposures among the study subjects and evaluate the potential brain tumour (i.e. glioma and meningioma) risk associated. Making use of the subjects' occupational histories, a modified version of the Finnish job-exposure matrix, FINJEM, was used to assess exposure to selected chemicals (Van Tongeren *et al.*, 2013). Similarly, an ELF-job-exposure matrix (JEM) (Bowman *et al.*, 2007), updated within the project, was used to assess ELF exposure (Turner *et al.*, 2014). However, the detailed information collected, including EMF sources, tasks, and work organization, allows for a more individualized exposure assessment for the study subjects.

The development of this new approach required the identification of source-based measurement data to estimate typical exposures associated with each source identified. Since these exposures may have happened a long time in the past, the collection of historical exposure data was essential. There are numerous published and unpublished documents in the literature with measurements for occupational EMF sources, such as the original articles by Conover *et al.* (1986) and Stuchly and Lecuyer (1989) and review articles by Mantiply *et al.* (1997) and Floderus *et al.* (2002). Environmental and industrial hygiene reports (e.g. Allen *et al.*, 1994; Cooper, 2002), with measurements for a variety of EMF sources, obtained for scientific or compliance purposes, also exist. Though they are rarely published and tend to be difficult to locate, being considered a type of 'grey literature' (Auger, 1998), they provide valuable information.

Taking advantage of the availability of this source-based data in the literature, and similarly to other exposure measurement databases constructed for retrospective occupational exposure assessment for agents such as asphalt (Burstyn *et al.*, 2000), rubber (De Vocht *et al.*, 2005), lung carcinogens (Peters *et al.*, 2012), or silica (Beaudry *et al.*, 2013), our aim was to systematically collect, critically review, and compile the available literature on exposure measurements for occupational sources of electric and/or magnetic fields between 0 Hz and 300 GHz, covering the entire EMF range. This paper describes the methodology used to conduct the literature review, assess the quality of the exposure data identified, and select and extract the measurement and complementary data into an Occupational Exposure Measurement Database (OEMD), as part of the INTEROCC Study exposure assessment approach (Fig. 1).

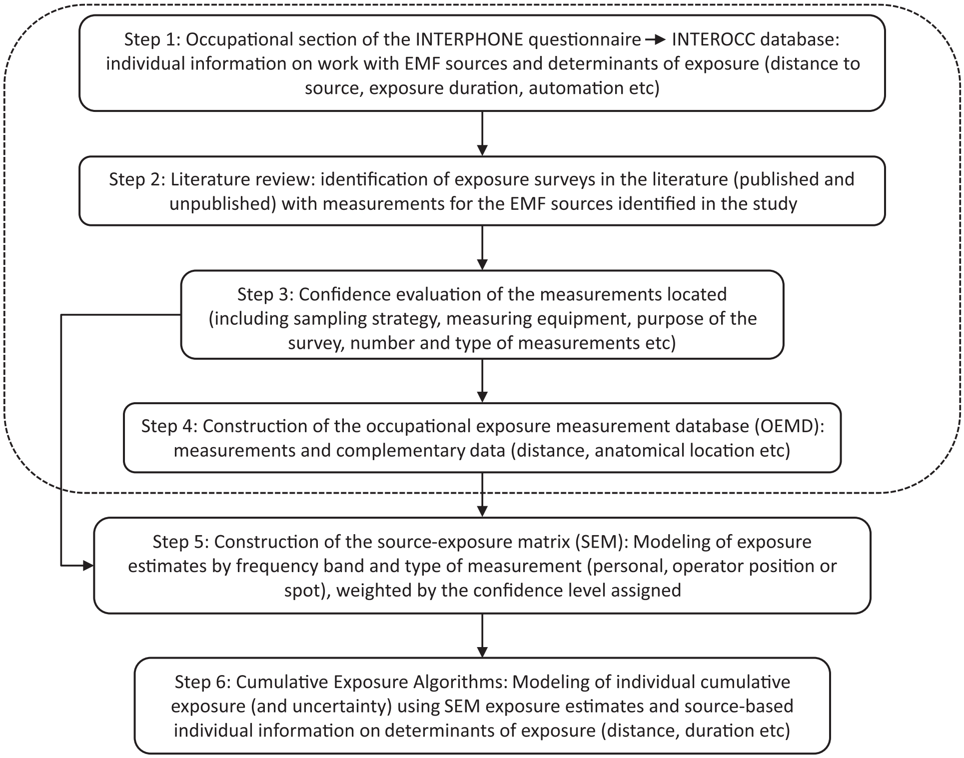

Figure 1 Overview of source-based occupational exposure assessment to EMF in INTEROCC. This flowchart outlines the different steps of the exposure assessment approach developed within the INTEROCC project. The current manuscript entails steps 1 through 4 which led to the development of the EMF Occupational Exposure Measurement Database (OEMD). Steps 5 and 6 will be described and published elsewhere.

METHODS

EMF sources in the OEMD

At the outset of INTERPHONE, a list of common occupational EMF sources were compiled, based on the literature and consultation with an EMF expert panel, consisting of scientists experienced in measuring and analysing workplace magnetic and/or electric fields. This list of sources formed the basis of the INTERPHONE EMF occupational questionnaire, which included 12 sections aimed at identifying workers with potentially high exposure to EMF in different occupational sectors, based on the sources to which they could be exposed (see Table 2). Each section flowed from an initial screening question towards more specific questions about particular sources of exposure and conditions of use. The source of exposure may have been either the equipment or process used (e.g. heating, sealing) or the tasks carried out in the vicinity of specific sources (e.g. repair tasks surrounded by emitting antennas). The questionnaire asked about equipment type, material being heated/sealed/bonded, as appropriate, distance to the source, start and end dates, and number of hours per day/week of use/exposure. This information was obtained for each job held 6 months or longer, using a computer-assisted personal interview (CAPI) system (see Supplementary Annex I).

In addition to this initial list of sources, all questions allowed for an 'other' response, which the interviewer entered into CAPI as free text. Following translation into English, hundreds of free text responses were reviewed and converted into unique source codes. For each source thus identified, we decided to: (i) discard if the source had no EMF emissions (e.g. flame welding); (ii) assign an existing EMF source; or (iii) assign a new EMF source. When text entries were not sufficiently clear, we used the subject's job title, company, and company activity (also free texts) and carried out a web search to identify the most likely source reported. This process led to the identification of a second list of workplace EMF sources.

Table 2. Description of occupational sections defined in INTEROCC and the frequency bands of the EMF sources encountered

Occupational section	Frequency band	Description[a]
Diagnosis and treatment	SMF, ELF, IF, RF	This section involves the use, maintenance, and repair of health devices for treatment (e.g. diathermy) or diagnosis (e.g. magnetic resonance imaging machines).
Electric company/ utility	ELF	Electric company or utility work encompasses a wide range of occupations. The main work categories may be considered in terms of the five main stages of electricity production and distribution (i.e. power stations, transmission lines, substations, distributions lines, and destination).
Electrician and electric equipment construction, repair and maintain	ELF	Working as an electrician covers a wide range of activities including setting up, maintenance and repair of electric installations in residences, commerce and construction sites. The construction, repair, testing, and maintenance of electric machinery or equipment cover a range of activities associated with the manipulation of electric devices.
Electric motors	SMF, ELF	Work with electric motors refers to the operation or monitoring of industrial machines which contain electric motors, including sewing machines and tools to perform repetitive work, such as lathes, presses, and drills.
Electric transport	SMF, ELF	Electric transport work involves the driving, maintenance, or staffing of vehicles powered by electricity, such as electric buses, trains, trams, and underground transport.
Heating food/ medical-dental	ELF, IF, RF	This section covers a range of activities where electric heating devices and machinery are used during heating, cooking, and curing of foodstuffs or for sterilization of medical and dental equipment.
Industrial heating	SMF, ELF, IF, RF	Industrial heating equipment refers to a range of machines used to heat materials such as metals, glass, ceramics, or rubber.
Radar	RF	Radar is a system for detecting objects (e.g. in the air, land, or at sea) using radio signals, usually by emitting a series of short pulses of radiofrequency energy. Forms of radar broadly include search radar (to give the approximate location of objects) and tracking radar (used to follow a target).
Semiconductors	ELF, IF, RF	The field of semiconductor/microelectronic manufacturing includes the development of components for computers (e.g. microchips), telecommunications equipment, and numerous other electronic devices.
Telecommunication antennas	ELF, IF, RF	This section refers to structures which use radiating electromagnetic waves for communication, including radio and television towers. Antennas may be described according to their use (e.g. TV, radio), shape, and the frequency of their signal (e.g. HF, VHF, UHF).

Table 2. *Continued*

Occupational section	Frequency band	Description[a]
Transmitters	ELF, IF, RF	Transmitters are electronic devices used in telecommunications to generate a radio frequency alternating current which with the aid of an antenna emit electromagnetic or radio waves. Transmitters are used in broadcasting, but also as components in mobile phones, wireless networks, Bluetooth, two-way radios etc.

HF, high frequency; VHF, very high frequency; UHF, ultra high frequency.
[a]See Supplementary Annex I for detailed information on each of the occupational sections defined in INTEROCC.

Retrieval of source-based EMF measurement data from the literature

A systematic search was conducted for documents in English dating from 1950 onwards (to include older devices used by study subjects) in order to locate measurement data for the EMF sources identified. As it is not clear whether newer technologies emit lower or higher EMF levels, no end limit was established for this search. The objective was to identify documents containing raw or summarized measurement data for occupational sources of electric and/or magnetic fields in the 0 Hz to 300 GHz frequency range.

Public access online databases were searched for both published articles and unpublished reports. They included those of the US National Library of Medicine (MEDLINE); the US National Institute for Occupational Safety and Health (NIOSH); the Canadian Centre for Occupational Health and Safety (CCOHS); the UK Health and Safety Executive (HSE), the US Environmental Protection Agency (EPA), and the International Labour Organization (ILO). Search engines linked to these databases, including PubMed, Toxline, HSELINE, NIOSHTIC, CISILO, OSHLINE, Scopus, and Web of Science, were used by inserting a series of keywords. Various combinations of keywords were entered, including the name of the source (e.g. radar, diathermy), and more general identifiers such as 'occupational', 'exposure', 'EMF', and/or 'measurement'. Access to measurements not publicly available was gained through the US National Institute for Occupational Safety and Health (NIOSH). In addition, we requested unpublished documents from EMF researchers and asked colleagues actively involved in EMF occupational surveys in different countries to make additional measurements for the sources identified in the study.

Confidence evaluation and inclusion criteria

The documents identified were peer-reviewed to select those relevant to the project aim and abstract the appropriate information. Each document was reviewed by two EMF experts, who completed confidence evaluation forms to assess the validity of the measurements for epidemiologic purposes, in terms of quality and relevance. The confidence evaluation process involved the assessment of the following eight factors: (i) sampling strategy; (ii) dosimetry type; (iii) anatomical location; (iv and v) number and type of measurements used to calculate the statistics provided; (vi) duty cycle (i.e. percentage of time that an equipment is powered on); (vii) nature of exposure scenarios; and (viii) reliability of the measuring process (e.g. type of equipment, calibration). If a document reported measurements taken with different strategies, instruments, or other factors that affected the confidence ratings, separate evaluations were conducted for each set of measurements (see Supplementary Annex II for the confidence evaluation form). Since levels associated with a particular EMF source are highly influenced by the dosimetry type used (i.e. spot, operator position or personal), a set of measurements was defined as a group of summary statistics for each electric or magnetic field for a specific EMF source, frequency band, and dosimetry type.

Based on these factors, each set of measurements was rated on a scale from 0 to 3. The average of the eight ratings was the final confidence value assigned to the set of measurements. Confidence levels were categorized as follows: <1 (low confidence); ≥1–2 (moderate confidence); and ≥2–3 (high confidence). Thus, poorly rated measurements (<1) were only included if they made a unique contribution to the exposure assessment. To ensure comparability between the raters, we performed duplicate assessments and, in case of major disagreements (i.e. ratings differing in more than one unit), had discussions among raters until reaching consensus.

Measurement data and complementary information included in the database

Measurements were abstracted, when available, for each of the E-, H-, and B-fields, as well as PD. When necessary, units were converted to the SI system. Values extracted were the minimum, the maximum, the arithmetic mean (AM) or time-weighted average (TWA), the geometric mean (GM) as well as outside dynamic range values (i.e. measurements below or above the limit of detection of the meters used, for example <0.1 μT or >200 V m^{-1}) and other statistics including standard deviations, when available.

Complementary information was also collected, since to summarize a person´s exposure to static and time-varying EMF in a single number, or 'exposure metric', the frequency, spatial, and temporal characteristics of the measurements must be specified. The magnitude of the electric or magnetic field is strongly influenced by the distance to the source as well as by the dosimetry type used. For operator position and personal measurements, the sham or actual anatomical location of the meter (e.g. head, chest or waist) specifies the worker's body part measured. Most measuring devices require <1 s (~0.1 s) to accurately record the root-mean-square of an arbitrary waveform. Sampling interval for personal measurements tends to be fixed (~1–10 s). Data are logged for several minutes providing a range of values which can also be averaged over the whole measurement duration. For spot and operator position measurements, sampling interval ranges between a few minutes and several hours (Bowman *et al.*, 1998)

As a result, the OEMD contains the following information for each combination of EMF source and frequency band: (i) EMF source name and details; (ii) frequency band and range; (iii) reference of the document from which the information was obtained; (iv) link to the confidence evaluation rating; (v) complementary information including distance, dosimetry type, anatomical location, number of measurements to calculate the statistics provided and duty cycle; and (vi) the actual measurements for each electric or magnetic field. Other relevant information was included as remarks. There was considerable variability in the parameters reported in the literature; hence information for all variables was not always available. Thus, sampling interval was not extracted as it was rarely available, while dosimetry type could not be retrieved for measurements obtained from review articles (see Supplementary Annex III for detailed information on the parameters in the database). Frequencies were categorized into six bands, based on the definitions by the International Telecommunications Union (ITU, 2008). These bands were linked with the four bands used by the European Commission's Scientific Committee on Emerging and Newly Identified Health Risks (SCENIHR, 2007). For the purpose of this project the IF band was defined as the range between 3 kHz and 10 MHz.

Quality control of data extraction and entry into the database

Individual forms with the same structure as the database were used to facilitate abstraction of both measurement data and complementary information. To check for extraction errors and wrong unit conversions, a revision of the data recorded in the forms was carried out before entering the information into the database. To ensure the quality of the entry process, all original documents were manually reviewed and all data entered into the database were verified, ensuring that the data included agreed with the original papers and reports.

Furthermore, an automated method was developed to allow a second verification of the measurement data in the database. Basic physical relations between the EMF magnitudes, such as B [μT] = μ_o H [A m^{-1}] (where the permeability of free space $\mu_o = 4\pi \times 10^{-7}$ H m^{-1}), were used to perform the automated checks, ensuring that these physical relations were not breached and that unit conversions carried out when necessary did not affect these relations (see Supplementary Annex IV for full details of the relationships and terminology used).

Statistical and graphical analysis

The aim of this paper is not to analyse the data in the OEMD but to describe its construction and content. However, to assess the overall confidence on the documents used, we calculated an average rating for each document based on the individual ratings assigned to the sets of measurements included. Then, we performed an analysis of the level of agreement using both the quantitative values provided by the experts and qualitative rankings by categorizing the original data. We analysed these data using both the weighted kappa and the intraclass correlation coefficient, to ensure their similarity (Fleiss and Cohen, 1973). Review articles were excluded from this analysis since they were assigned a rating of 1.

As an example of the OEMD's capabilities, we plotted the data for electric and magnetic field levels versus distance for selected sources. To illustrate EMF's characteristic inverse distance relationships to their source (constant × d^{-n} for $n = 0$ to 3 or more, depending on source design), we fitted linear models to our log-transformed data and plotted the anti-logs. These graphs illustrate the classic inverse distance (d^{-n}) patterns that have been found for ELF magnetic fields from appliances (Preece *et al.* 1997; Maslanyj and Allen, 1998; Leitgeb *et al.*, 2008) and RF electric fields from antennas (Hankin, 1986). At distances far from ELF sources with simple geometry, the exponent n goes from 1 to 3 as the amount of cancellation among the magnetic field vectors from the individual wires increases (Bowman, 2014). In the far field of simple RF antennas, the electric field's exponent is 1 (Hankin, 1986). All analyses and graphs were performed using RStudio© version 0.98.1103.

RESULTS

As of September 2015, the OEMD contains 1624 sets of measurements for 285 EMF source and frequency band combinations. From 114 documents located in the literature with measurements for the EMF sources identified, 95 were selected to be used in the construction of the database. The remaining documents were excluded for various reasons (see Supplementary Annex V for details of the documents included and excluded and reasons for their exclusion). Sixty four of the documents were articles, mostly published in peer-reviewed journals and also some unpublished ($n = 3$), and 33 (~35%) were 'grey literature' resources (i.e. occupational or environmental technical reports either publicly available through their respective working groups or obtained by other means). Nearly half of the measurements abstracted ($n = 748$) were obtained from these 'grey literature' resources. Only one researcher (Minerva Yue) provided measurements ($n = 20$) from an ELF survey performed in Cincinnati, USA (Reference: Yue 04). Figure 2 describes the number and type of documents identified and included or excluded at each step of the literature review.

The database contains a total of 3141 entries, almost double the number of sets of measurements, since each set of measurements may contain one or more statistics. Supplementary Table I describes the number of entries in the database by type of statistic provided, field and dosimetry type. Maximum values for spot or operator position dosimetry ($n = 930$) were provided far more often than any other type of statistic. Area measurements (i.e. spot and operator position) were more frequently provided ($n = 2215$) than personal measurements ($n = 307$). The maximum was the most frequently provided statistic for B-, H-, and E-fields ($n = 1170$), whereas mean (AM or TWA) was only commonly provided for B-field ($n = 436$). Other statistics such as GM were also frequent for B-field measurements ($n = 59$), while values outside the dynamic range of the instruments used were more often provided for E- and H-fields ($n = 73$). Source-based measurements in the literature tend to be reported as spot measurements ($n = 788$) followed by measurements at the operator position ($n = 543$) and finally personal measurements ($n = 190$). More than 50% of the personal measurements were made in electric utilities ($n = 100$) (Supplementary Table II). Within the RF range, we collected measurements for 68 sources (Table 3). In the SMF and ELF bands, we identified measurements for 183 sources, while in the IF band we abstracted measurements for 34 sources. Table 3 also summarizes the period of time covered by the database (1974–2013, with one paper from 1969) as well as the origin of the measurements collected (16 different countries: Australia, Belgium, Canada, Denmark, Finland, Italy, Japan, the Netherlands, New Zealand, Norway, Poland, Sweden, Switzerland, Taiwan, UK, and USA). Measurements extracted are mainly for sources used in the 1990s and 2000s (~67% of the documents), while only ~33% of the documents refer to sources used in the late 1970s and 1980s.

A total of 268 confidence evaluations were obtained from 12 different raters. Many documents obtained two or more ratings since they comprise several sets of measurements. Due to the limited availability of the expert panel, a few documents ($n = 3$), with measurements for an unusually large number of sources,

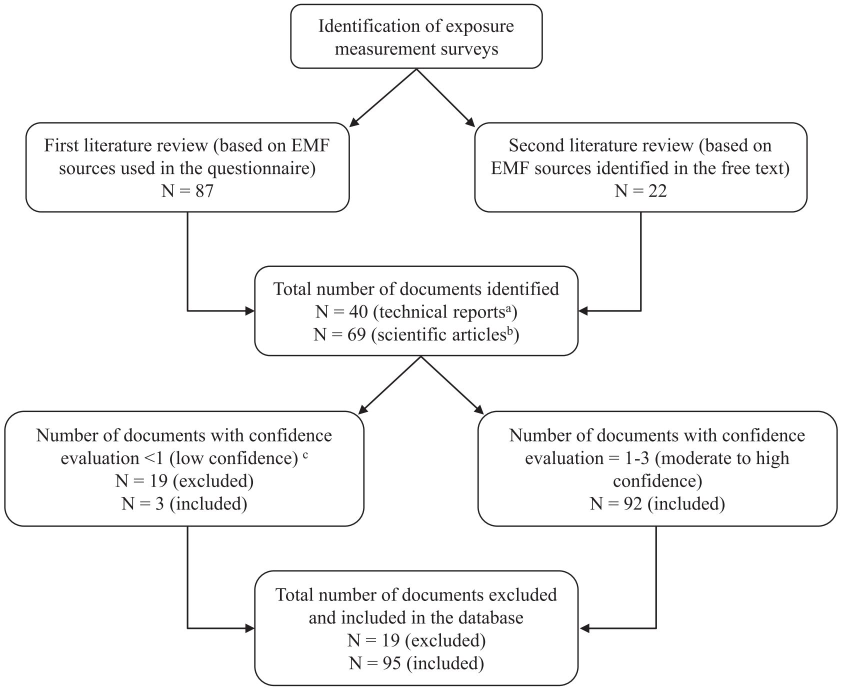

Figure 2 Description of the literature review performed to construct the OEMD. This flowchart describes the different steps and number of documents identified, included and excluded throughout the literature review carried out to construct the OEMD. (a) This figure includes some books, book chapters or actual measurements (n = 5). (b) This figure includes both published (n = 59) and unpublished articles (n = 3). (c) This rating refers to the full document or sets of measurements within the document. As stated in the text, documents with a rating <1 were included in the database if they made a unique contribution to the exposure assessment.

obtained only one rating per set of measurement. We asked the experts to reach a consensus evaluation for only five sets of measurements. Less than 8% of the documents (n = 7) were rated <1 (low confidence). Around 60% (n = 53) were above 2 (high confidence), while the overall mean rating for all the documents in the database was 1.92 (moderate to high confidence). The analysis of agreement between raters, based on the average ratings by paper, showed substantial agreement (Teschke *et al.,* 2002): intraclass correlation coefficient (ICC = 0.767; 95% confidence interval (CI) = 0.518–0.881; P < 0.0001) and a weighted kappa (κ = 0.637; P < 0.0001). The categorization of the continuous ratings did not affect the comparison since κ value is included in the ICC 95% CI.

Concerning distance, we collected vertical distance data for 53 EMF sources and horizontal data for 129 sources (spot measurements). Data on anatomical location (e.g. head, chest, or waist) were obtained for 552 sources (personal and operator position). Figure 3 describes the effect of distance on B- and E-field spot measurements near selected ELF and RF sources. Measurements near EMF sources fit the general pattern of decline, although the exponents n often diverge from theory due to their complicated wiring. The examples of typical domestic ELF sources in Fig. 3A show the expected decline but had exponents ranging from 1.08 (coffee machine) to 2.14 (induction plates). The exponents for RF electric fields (Fig. 3B) were 0.53 (paging antenna) and 2.01 (diathermy), which are again in qualitative agreement with theoretical expectations.

DISCUSSION

After an extensive literature review, a database of source-based measurements for occupational exposure to electric and magnetic fields was constructed. This database contains measurements for the most common sources of EMF in the workplace, based on the INTERPHONE-INTEROCC study questionnaire.

Table 3. EMF sources in the OEMD by occupational section, frequency band, reference, and country of origin of measurement data

Occupational section	Frequency	EMF sources in the database (examples)	#Sources[a]	References	Countries
Diagnosis and treatment	SMF, ELF	MRI, magnetic, and electrostimulation therapy	6	Allen *et al.*, 1994;[b] Bracken *et al.*, 1994; Di Nallo *et al.*, 2008; Floderus *et al.*, 2002; Hagmann *et al.*, 1985; Liljestrand *et al.*, 2003; Maccà *et al.*, 2008; Mantiply *et al.*, 1997; Martin *et al.*, 1990; Mild, 1980; Moseley and Davison, 1981; Shah and Farrow, 2013; Smith *et al.*, 1984; Stuchly et al., 1982, 1983	Canada, Italy, Sweden, UK, USA
	IF	MRI, surgical and ultrasound diathermy	6		
	RF	Hyperthermia, shortwave, and microwave diathermy	9		
Electric utility	ELF	Electric meter, power station, high voltage transmission lines, substations/switchyards, turbine hall, boiler house, underground power lines, workshops, control room, distribution lines	21	[b]Bowman *et al.*, 2004; Bowman *et al.*, 1988; Bracken, 2002; Bracken *et al.*, 1997; Cooper, 2002; Deadman *et al.*, 1996; Dillon and von Winterfeldt, 2000; Renew *et al.*, 2003; Sakurazawa *et al.*, 2003; Skotte, 1994	Canada, Denmark, Japan, UK, USA
Electrician and electric equipment construction, repair and maintain	ELF	Home entertainment equipment, office machines, electric utility (repair)	3	Bowman *et al.*, 1988; [b]Yue *et al.*, 2004	USA
Electric motors	SMF, ELF	Metal electroplating, laundry equipment, lawnmower, meat slicer, pipe threader, milking machine, packaging equipment, food mixer	92	Allen *et al.*, 1994; Bowman and Methner, 2000; Bowman *et al.*, 1988; Breysse *et al.*, 1994; Di Nallo *et al.*, 2008; Gauger, 1985; Hansen *et al.*, 2000; [b]Hogue *et al.*, 1995; Huang *et al.*, 2011; [b]Jonker *et al.*, 2005; Kelsh *et al.*, 2003; Maslanyj and Allen, 1998;	Canada, Italy, the Netherlands, Taiwan, UK, USA

Table 3. *Continued*

Occupational section	Frequency	EMF sources in the database (examples)	#Sources[a]	References	Countries
				Methner and Bowman, 2000; Preece *et al.*, 1997; Renaud and Bousquet, 1999; [b]Tell *et al.*, 1990; [b]Yost *et al.*, 2000; [b]Yue *et al.*, 2004	
Electric transport	SMF, ELF	Train, maglev train, metro, electric delivery trucks, electric/hybrid cars, tram, shuttle tram/ people mover	12	Allen *et al.*, 1994; Dietrich and Jacobs , 1999; Goellner *et al.*, 1993; Halgamuge *et al.*, 2010; Minder and Pfluger, 1993; Wenzl, 1997	Australia, Switzerland, UK, USA
Heating food and medical–dental	ELF	Deep fat fryer, oven, microwave oven, food warmer, hair dryer, fan heater, autoclave/sterilising equipment	18	Allen *et al.*, 1994; Elder *et al.*, 1974; Gauger, 1985; [b]Hogue *et al.*, 1995; Mantiply *et al.*, 1997; Preece *et al.*, 1997; Renaud and Bousquet, 1999; Rose *et al.*, 1969; Stuchly and Lecuyer, 1987; [b]Yost *et al.*, 2000; [b]Yue *et al.*, 2004	Canada, UK, USA
	IF	Induction plates	1		
	RF	Microwave oven and microwave oven repair	2		
Industrial heating	SMF, ELF	Soldering, MMA, MIG/MAG, TIG, and SA arc welding, resistance welding, induction heater/ furnace, resistance furnace	18	Allen *et al.*, 1994; Andreuccetti *et al.*, 1988; Bini *et al.*, 1986; Bowman *et al.*, 1988; Chadwick, 1997; Conover *et al.*, 1980; Conover *et al.*, 1986; Conover *et al.*, 1992; Conover *et al.*, 1994; Cooper, 2002; Floderus *et al.*, 2002; Hietanen *et al.*, 1979; Hitchcock *et al.*, 1995; [b]Jonker *et al.*, 2005;	Australia, Canada, Denmark, Finland, Italy, the Netherlands, Sweden, UK, USA
	IF	Induction welding and soldering, dielectric heater, glue heater curer, high frequency arc welding	8		
	RF	Turntable unit, shuttle tray machine, RF sealer, pressure sealed applicator, microwave heating for ceramics	7		

Table 3. *Continued*

Occupational section	Frequency	EMF sources in the database (examples)	#Sources[a]	References	Countries
				Joyner and Bangay, 1986; Lovsund *et al.*, 1982; Mantiply *et al.*, 1997; Methner and Bowman, 2000; Moss and Mattorano, 1994a, b; Repacholi, 1983; Skotte and Hjøllund, 1997; Stuchly *et al.*, 1980; Stuchly and Lecuyer, 1985; Stuchly and Lecuyer, 1989; Wilén *et al.*, 2004; [b]Yost *et al.*, 2000; [b]Yue *et al.*, 2004	
Radar	RF	Air traffic control, aircraft radar (e.g. weather), speed detector (hand-held and fixed on a vehicle), marine radar, navigation radar, security radar,	14	Allen *et al.*, 1994; Baste *et al.*, 2010; [b]Bernhardt *et al.*, 1992; [b]Bitran *et al.*, 1992; [b]Bradley *et al.*, 1991; Degrave *et al.*, 2009; [b]Fisher *et al.*, 1991; Hankin, 1986; Lotz *et al.*, 1995; Mantiply *et al.*, 1997; [b]Peak *et al.*, 1975; Szmigielski, 1996; Tell and Nelson, 1974a, 1974b; [b]Tell *et al.*, 1976	Belgium, Canada, Norway, Poland, UK, USA
Semiconductors	ELF	Ion implantation, plasma etcher, sputtering, aligners, diffusion furnace	11	Abdollahzadeh *et al.*, 1995; Bowman *et al.*, 1988; Cooper, 2002; Floderus *et al.*, 2002; Rosenthal and Abdollahzadeh, 1991; Ungers *et al.*, 1984	Sweden, UK, USA
	IF	Plasma-enhanced chemical vapour deposition (CVD), plasma etcher	2		
	RF	Plasma asher/ stripper, plasma etcher, CVD	4		
Telecommunication antennas	ELF	Marine-naval radio antenna	1	Allen, 1991; Allen *et al.*, 1994; [b]Anderson *et al.*, 1999; Baste *et al.*, 2010;	Denmark, New Zealand, Norway, UK, USA

Table 3. *Continued*

Occupational section	Frequency	EMF sources in the database (examples)	#Sources[a]	References	Countries
	IF	AM radio antennas, LF and VLF radio station antenna, navigation antenna,	11	[b]Cleveland *et al.*, 1995; [b]Conover *et al.*, 1999; Cooper *et al.*, 2007; Mantiply *et al.*, 1997; [b]Moss *et al.*, 1999; Skotte, 1984; Sylvain *et al.*, 2006; Tynes *et al.*, 1996	
	RF	Marine-naval radio antenna, FM radio antenna, mobile phone base station antenna, roof-top paging antenna, UHF, and VHF TV antenna	25		
Transmitters	ELF	Metal detectors, EAS systems, demagnetizers	3	Allen *et al.*, 1994; Cooper, 2002; Di Nallo *et al.*, 2008; [b]Jonker *et al.*, 2005; Joseph *et al.*, 2012; Lambdin, 1979; Mantiply *et al.*, 1997; [b]Ruggera *et al.*, 1979; Sylvain *et al.*, 2006; [b]Yost *et al.*, 2000	Belgium, Italy, the Netherlands, UK, USA
	IF	Electronic Article Surveillance (EAS) systems, metal detectors	4		
	RF	two-way radio, walkie-talkie, cordless telephone (DECT and non-DECT), CB radios, car radios	7		

MRI, magnetic resonance imaging; MMA, manual metal arc; MIG/MAG, metal inert/active gas TIG, tungsten inert gas; SA, submerged-arc. VHF, very high frequency; UHF, ultra high frequency.
[a]The number of EMF sources in the OEMD for each occupational section and frequency band also comprises different situations/tasks in which these sources are used (scenarios). Therefore, the total number of sources, including scenarios, includes more sources than those listed under the third column of this table.
[b]References unobtainable by readers (obtained directly from the authors or by other means as explained in the text). The full reference for these citations can be consulted in Annex V of the Supplementary Material.

Putting together data from multiple exposure measurement studies, we covered multiple exposure situations, increased representativeness, and allowed easy access to information on a large variety of sources of exposure, from SMF (0 Hz) to RF (up to 300 GHz). The use of unpublished technical reports and other types of 'grey literature' was essential for the identification of measurement data not found elsewhere (almost 50% of the measurements in the database were unpublished), confirming that, although sometimes difficult to locate, these literature resources represent an important source of information and should not be discarded when constructing exposure measurement databases. The great number of unpublished measurements identified also highlights the need to publish these data in the peer-reviewed literature.

EMF sources included in the database were both identified *a priori* by the INTEROCC expert panel

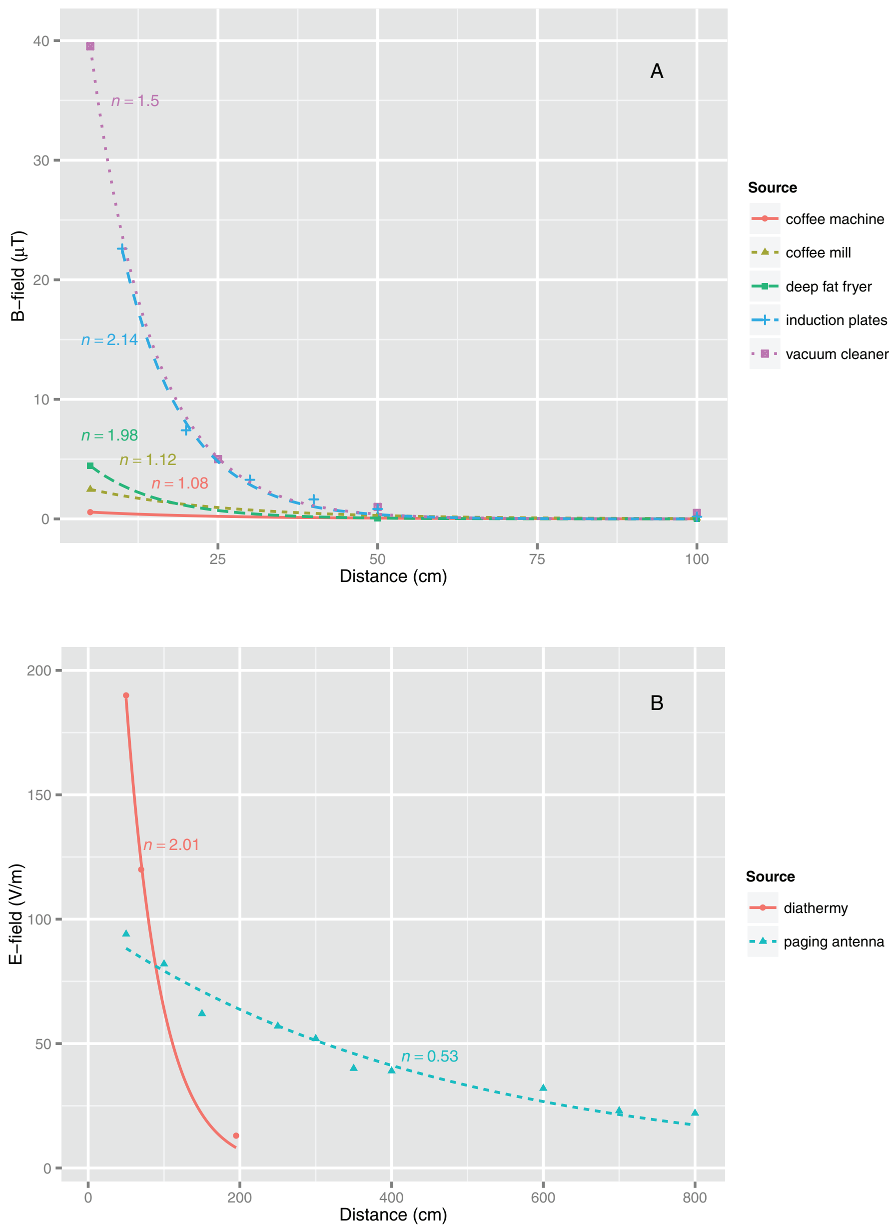

Figure 3 B-field versus distance for ELF (50/60 Hz) sources (A) and E-field versus distance for RF sources (continuous shortwave diathermy, 27.12 MHz and roof-top paging antenna, 678.4 MHz) (B). The EMF magnitudes available in the OEMD were fit by regression techniques to functions of the inverse distance = constant × d^{-n}.

and reported by the study subjects (over 10 000 workers from seven different countries). However, despite its size and the number of EMF sources covered, the OEMD entails several limitations. It is possible that some EMF sources may be missing, although these are likely to be relatively rare sources of exposure to EMF. Although the number of measurements for some sources is limited, the database is open to the addition of more measurements and sources in the future, either from field surveys or new and non-identified literature resources.

The confidence evaluation process aimed at evaluating the quality and relevance of the measurements to represent EMF personal exposure at work. However, one of the factors assessed in this process (i.e. anatomical location) was not specific to quality control, since it was included to estimate the relevance of the measurements for the purpose of the INTEROCC study. Although the inclusion of this factor in the assessment process may have altered the results slightly, its impact can be considered low in the light of the remaining seven factors that were specifically established to evaluate the quality of the measurements. Another possible weakness relates to the averaging approach followed to calculate the final mean rating over all eight factors. This could potentially have included errors, since low ratings assigned to one or more factors get diluted by higher ratings assigned to the rest. Thus, high confidence could be assigned to a set of measurements obtained with bad quality or uncalibrated equipment which scored well in the remaining factors. However, we did not find that this potential pitfall occurred in any of the evaluations performed.

Unlike job-exposure matrices (JEMs), which can be easily used to infer exposures with knowledge of the subjects' occupational titles, the source-based assessment approach requires both the development of exposure estimates (i.e. construction of a summarized exposure matrix by source) and the availability of detailed information on the determinants of exposure (e.g. distance to the source, frequency and duration of use/exposure). This information needs to be collected before exposure levels can be assigned to study subjects, which makes the OEMD, and the upcoming source-exposure matrix (SEM) to be constructed from it, useful for future studies where source-based information is collected. For this purpose, we have provided the detailed source-based questionnaire used in INTEROCC as Supplementary Data with this paper. We expect that its use and potential improvement may encourage the collection of the required source-based information in future EMF studies. Moreover, since the combination of measurements and questionnaires can reduce bias and uncertainty due to measurement errors (Burstyn, 2011), the development of methods with higher validity and reliability is envisaged with the use of both an ongoing improved OEMD and an enhanced questionnaire.

Despite the above limitations, the OEMD also entails several advantages. This database satisfies the highlighted need for knowledge of the contribution from each source to the average EMF exposure (Savitz, 1995), as well as the required compilation of exposure data for occupational sources of EMF (Stam, 2014). Some authors have also fostered the development of new strategies for occupational exposure assessment (Savitz, 1995; Teschke *et al.*, 2002), incorporating variations on the more traditional measurement-based job-exposure matrices. Since a person's occupational exposure depends on the strength of the EMF sources, as well as other determinants (e.g. distance to the source, proportion of time spent near the source), individual EMF exposure can widely vary among occupational groups (Kheifets *et al.*, 2009). Therefore, JEMs tend to misclassify individuals within the same groups (i.e. job titles), whereas the source-based approach may increase the ability to disentangle the exposure variability among individuals.

Rajan *et al.* (1997) proposed the basic core information necessary when reporting exposure measurement data. Although this and other proposals have been developed for chemical agents, they are also applicable for EMF and other physical agents, and can help improve the validation and harmonization of collected information on occupational exposure data. Distance to the source, dosimetry type, and anatomical location are among the most important determinants of exposure with regard to EMF sources (Röösli, 2014). Therefore, when available, we collected information on both the horizontal and vertical distance from the meter (i.e. spot and operator position measurements) and the anatomical location in relation to the subject (i.e. operator position and personal measurements). Thus, the collection of complementary data on distance and anatomical location by dosimetry type, together with other relevant data (e.g. duty cycle, source details, number of measurements), allowed the provision of adequate information for the storage and exchange of EMF exposure data.

The values in this database are summary statistics obtained from diverse measurement surveys, performed for particular purposes (e.g. compliance, scientific use) and specifications (e.g. type of equipment, sampling strategy). Their validity is therefore influenced by the quality and characteristics of the methods used. In the interest of greater transparency concerning quality and relative value of exposure data (Tielemans *et al.*, 2002), the OEMD not only reports the measurement values and complementary information, but also our assessment of confidence in those values. At the moment, no validated method to assess the quality of exposure data exists, yet some authors (Tielemans *et al.*, 2002) have proposed the evaluation of precision, validity, and availability of complementary data. The factors included in the confidence evaluation process are expected to cover these and other more specific aspects of EMF exposure assessment, ensuring that the measurements in the database are the best currently available.

The OEMD has been developed for its use within the framework of an epidemiological study, INTEROCC. The data it contains will be used to develop an SEM, to be described and published elsewhere. This exposure tool will contain confidence-weighted summarized exposure estimates by source, and will be used to assign exposures to the INTEROCC study subjects based on the EMF sources reported. The SEM will also be used in other epidemiological studies, where a similar source-based approach has been followed (e.g. Mobi-Kids: Sadetzki *et al.*, 2014). However, the information in the OEMD can also be useful for occupational hygiene purposes, through the identification of EMF sources with substantial exposure levels on which to focus control measures. Recently, Stam (2014) assembled available measurements in the literature for EMF sources up to 10 MHz, in an effort to compare the levels encountered in European workplaces and the limits established in the new revised EMF EU Directive (EU, 2013). The information in the OEMD will assist similar upcoming efforts comparing legally established limits with typical exposure levels in the workplace, and other occupational hygiene assignments where EMF exposure data by source are needed.

In conclusion, in this paper we have presented the methods and results of constructing a source-based database with measurements for occupational sources of EMF exposure from the literature, covering the frequency range from 0 Hz to 300 GHz. To our knowledge, this database represents the most comprehensive resource of measurements available and an innovative approach for occupational exposure assessment, based on sources of EMF exposure regardless of occupation. Both the OEMD and the SEM to be developed from it will be offered for use by other researchers, optimizing the usefulness of the work we have conducted in improving occupational EMF exposure assessment and keeping the database content up to date. The OEMD is publicly available at www.crealradiation.com/index.php/en/databases. Filtering the information in the different tables will allow the identification of the collected measurements for specific EMF sources and frequency bands, as well as relevant complementary information.

SUPPLEMENTARY DATA

Supplementary data can be found at http://annhyg.oxfordjournals.org/.

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