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Original Article

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Development of a Job-Exposure Matrix for Assessment of Occupational Exposure to High-Frequency Electromagnetic Fields (3 kHz–300 GHz)

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Abstract

Objectives: The aim of this work was to build a job-exposure matrix (JEM) using an international coding system and covering the non-thermal intermediate frequency (IF) (3–100 kHz, named IFELF), thermal IF (100 kHz–10 MHz, named IFRF), and radiofrequency (RF) (>10 MHz) bands.

Methods: Detailed occupational data were collected in a large population-based case–control study, INTEROCC, with occupations coded into the International Standard Classification of Occupations system 1988 (ISCO88). The subjects' occupational source-based ancillary information was combined with an existing source-exposure matrix and the reference levels of the International Commission on Non-Ionizing Radiation Protection (ICNIRP) for occupational exposure to calculate estimates of level (L) of exposure to electric (E) and magnetic (H) fields by ISCO88 code and frequency band as ICNIRP ratios (IFELF) or squared ratios (IFRF and RF). Estimates of exposure probability (*P*) were obtained by dividing the number of exposed subjects by the total number of subjects available per job title.

Results: With 36 011 job histories collected, 468 ISCO88 (four-digit) codes were included in the JEM, of which 62.4% are exposed to RF, IFRF, and/or IFELF. As a reference, *P* values for RF E-fields ranged from 0.3 to 65.0% with a median of 5.1%. *L* values for RF E-fields (ICNIRP squared ratio) ranged from 6.94×10^{-11} to 33.97 with a median of 0.61.

Conclusions: The methodology used allowed the development of a JEM for high-frequency electromagnetic fields containing exposure estimates for the largest number of occupations to date. Although the validity of this JEM is limited by the small number of available observations for some codes, this JEM may be useful for epidemiological studies and occupational health management programs assessing high-frequency electromagnetic field exposure in occupational settings.

Keywords: exposure estimates; IF; intermediate frequencies; JEM; radiofrequencies; RF; workers

Introduction

Electromagnetic fields (EMF) originate from charged particles and comprise a form of energy which travels through space (vacuum) at the speed of light. EMF can be characterized by their frequency, in Hertz, and amplitude. High-frequency electric (E) and magnetic (H) fields can be classified into an intermediate frequency (IF) range, from 3 kHz to 10 MHz, and a radiofrequency (RF) range, from 10 MHz to 300 GHz. This frequency classification and the nomenclature used are based on the definitions by the International Telecommunication Union (ITU, 2008). The term 'intermediate frequency' has become common in recent years to identify specific EMF sources such as induction cookers and anti-theft gates (SCENIHR, 2015). Many industrial and commercial activities lead to occupational exposure to high-frequency EMF, such as induction heating (for domestic and industrial use), remote detection of objects and persons (e.g. anti-theft gates, radars, radiofrequency identification devices), telecommunications (e.g. radio and television broadcasting, mobile phones, wireless networks), or medical therapy (e.g. diathermy equipment, electrosurgical devices) (Hitchcock, 2004).

Due to the increasing development of technologies emitting IF and/or RF EMF, high-frequency EMF are a growing potential occupational hazard. The International Commission on Non-Ionizing Radiation Protection (ICNIRP) establishes guidelines for limiting workers exposure to EMF. ICNIRP provides two kinds of limits, named 'basic restrictions' and 'reference levels', on the basis of established adverse health effects caused by EMF exposure, which include electrical stimulation of nerves and muscles for frequencies < 10 MHz, and excessive tissue heating for frequencies > 100 kHz. Both effects are considered for frequencies between 100 kHz and 10 MHz (ICNIRP, 1998, 2010). Beyond these well-known biophysical effects, epidemiological and experimental studies to date provide some evidence for a potential relationship between RF exposure and several adverse health effects, including cancer (Grayson, 1996; Szmigielski, 1996; Stang *et al.*, 2001), cardiovascular (Wilén *et al.*, 2007), pregnancy (Taskinen *et al.*, 1990; Mjøen *et al.*, 2006; Baste *et al.*, 2012), and fertility (Baste *et al.*, 2008; Møllerløkken and Moen, 2008) disorders. In 2011, the International Agency for Research on Cancer (IARC) classified RF as a 'possible human carcinogen' (Group 2B), based on 'limited evidence' from both human and animal studies investigating either mobile phone use or RF EMF exposure (IARC, 2013). The epidemiological evidence for occupational RF EMF exposure was considered inadequate due, in part, to exposure assessment limitations and small sample sizes available in previous studies. Recently, an expert advisory group recommended the re-classification of RF by IARC (with high priority), on the basis of newly available animal and mechanistic evidence (IARC Monographs Priorities Group, 2019).

In most occupational studies, exposure assessment was based on job descriptions or self-reported use or proximity to RF/IF sources, which may be affected by information biases (Ahlbom *et al.*, 2004). Other epidemiological studies used expert judgment, by providing an exposure probability based on available information of the worker's potential exposure (Berg *et al.*, 2006; Baldi *et al.*, 2011). Expert judgment is advantageous over self-reported data for evaluating occupational exposures (Teschke *et al.*, 2002) but is time-consuming and expensive to obtain exposure estimates in large population-based studies (Peters et al., 2011, 2014), and is generally considered to provide less reliable exposure estimates than using measurements (Kromhout, 2002). In a small number of studies, measurements obtained from workplaces were used to obtain estimates of the individual RF exposure or dose, to identify the groups of most highly exposed workers (Wilén *et al.*, 2004; Garaj-Vrhovac *et al.*, 2011; Bortkiewicz *et al.*, 2012; Wang *et al.*, 2016), or to compare the workers' exposure levels to ICNIRP guidelines or other safety limits (Chen *et al.*, 2013; Singh *et al.*, 2015; Singh and Kapoor, 2015). However, since obtaining measurements for each participant in large population-based studies requires heavy logistics and costs (Röösli and Vienneau, 2014), other methods to estimate past exposures, such as job-exposure matrices, are needed.

Although, to our knowledge, no specific RF-JEM exists in the literature, the Finnish general JEM, FINJEM (Kauppinnen *et al.*, 1998), contains some estimates of RF exposure (in W/m^2) by job code using the Finnish classification of occupations. However, FINJEM only provides estimates of prevalence and intensity of exposure to RF electric fields for four potentially exposed occupations. An Australian radiation JEM, AUSRAD, was developed to assess ionizing and non-ionizing radiation occupational exposure (Karipidis *et al.*, 2008). This JEM provides information for only three occupations exposed to RF. Other efforts include the recently released results of an Israeli National Survey (Hareuveny *et al.*, 2015), where almost 4300 measurements were performed in five large industries associated with RF exposure (i.e. industrial heating, communications, radars, research, and medicine), covering 25 occupations (or tasks). Results were expressed as percentages of the American Conference of Governmental and Industrial Hygienists (ACGIH) threshold limit values, although no standard occupational coding system was used.

As part of the multinational, population-based case–control INTEROCC study, a database with EMF measurements extracted from the literature, and a subsequent source-exposure matrix (SEM) combining all these measurements by EMF source and frequency, were recently constructed (Vila et al., 2016, 2017). The SEM and the detailed occupational histories collected in INTEROCC provided a unique opportunity to create a high-frequency EMF JEM (hereafter, RF-JEM). This article describes the methodology and content of this JEM, covering the non-thermal IF (3–100 kHz, named IFELF), thermal IF (100 kHz–10 MHz, named IFRF), and RF (>10 MHz) bands. These bands were defined on the basis of different well-known adverse health effects associated with EMF exposure of different frequencies (i.e. electrical stimulation of nerves and muscles for frequencies < 10 MHz, and excessive tissue heating for frequencies > 100 kHz).

Material and methods

The INTEROCC data

The INTEROCC study is a multinational, population-based, case–control study involving seven countries (Australia, Canada, France, Germany, Israel, New Zealand, and the UK) of the 13 included in the larger INTERPHONE study on central nervous system tumors in relation to mobile telephone use (Cardis *et al.*, 2007). The objective of the INTEROCC study was to address questions about the role of various occupational agents, including EMF and chemicals, in glioma and meningioma risk. Detailed occupational data were recorded by computer-assisted personal interviews. Information included job titles, company name and description, start and end year for all jobs held by the participant for 6 months or longer and details about tasks and EMF sources worked with or in proximity. Job titles were coded into the International Standard Classification of Occupations systems from 1968 (ISCO68), with three or five-digit codes, and 1988 (ISCO88), with two, three, or four-digit codes. For each job held by the participant, data on RF and/or IF sources were recorded using a questionnaire divided into seven occupational sections or modules: (i) medical diagnosis and treatment, (ii) heating food equipment (to cook, dry, sterilize, or pasteurize food), (iii) industrial heating, (iv) semiconductors manufacturing, (v) radars, (vi) telecommunication antennas, and (vii) transmitters (this module refers only to portable transmitters such as CB radios, walkie-talkies, DECT, and mobile phones). Consequently, the same job code may be associated with several occupational modules. Details of the information collected in each module are available elsewhere (Vila *et al.*, 2016).

Calculation of ICNIRP ratios from SEM mean estimates

The SEM mean estimates of all sources reported by an INTEROCC subject in a given job code were combined to obtain personal estimates of exposure intensity for IFELF, IFRF, and RF bands. Since well-known biophysical responses to EMF exposure are frequency dependent and RF and IF sources within the same frequency band (i.e. RF, thermal IF, and non-thermal IF) may have different frequency ranges (e.g. RF sources may have frequencies in the kHz, MHz, or GHz ranges), the aggregated effect of these combined exposures need to take these differences into account. For this purpose, ICNIRP frequency-specific reference levels (RLs) for occupational exposure, which are piecewise functions of frequency obtained from thresholds of biological responses, or 'basic restrictions' (ICNIRP, 1998), were used to obtain ratios of each SEM mean estimate for both electric (E) and magnetic (H) fields to the corresponding ICNIRP reference levels. Thus, ICNIRP ratios were calculated for frequencies below 100 kHz (IFELF) (equation 1), while ICNIRP squared ratios were computed for frequencies above this threshold (IFRF and RF) (equation 2):

$$\text{ICNIRP} \quad \text{ratio}_{G_s(f)} = \frac{\left[\overline{G_s}(f)\right]}{\left[\overline{G_{RL_s}}(f)\right]} \propto Ei \tag{1}$$

$$\text{ICNIRP} \quad \text{squared} \quad \text{ratio}_{G_s(f)} = \frac{\left[\overline{G_s}(f)\right]^2}{\left[\overline{G_{RL_s}}(f)\right]^2} \propto \text{SAR} \tag{2}$$

where G = E- or H-field for source s with frequency f; $\overline{G_s}(f)$ is the arithmetic mean exposure level for source s and frequency f obtained from the SEM, and $G_{RL_s}(f)$ is the ICNIRP occupational reference level for source s with frequency f. ICNIRP ratios are assumed to be proportional to internal electric fields (E_i), while squared ratios are assumed correlate with specific absorption rate (SAR). For example, the squared ICNIRP ratio for the RF source 'plastic sealer' would be $56.6 = \frac{459^2}{61^2}$, assuming a single frequency of 27 MHz, a reference level of 61 V/m, corresponding to this frequency, and an arithmetic mean operator position exposure level of 459 V/m, obtained from the SEM. See Supplementary Material, Part A (available at *Annals of Occupational Hygiene* online) for details on this calculation when a frequency range rather than a single frequency is considered for a particular EMF source.

Occupational exposure span

The exposure span is the combination of exposure duration (in years) and exposure rate (in hours per day or week). Study participants were asked to report the time they worked with or nearby the reported RF/IF source(s) in each job j and occupational module m during a typical work shift ($t_E[j,m]$ expressed in hours per day or week, depending on the information provided). The rate (or proportion of time that RF/IF exposure occurred during each job j and module m) (rate[j,m]) was then calculated depending on whether the information was provided per day or week ($rate_d = t_E/8h$ for a day work shift and $\text{rate}_w = t_E/40h$ for a week work shift). For example, one participant declared working with diathermy equipment in the 'medical diagnosis and treatment' module 7 h a day. Thus, his/her rate_d was 7/8 = 0.875. Since rate data were collected by job rather than by source, rate_d and rate_w were divided by the total number of RF/IF sources reported in each job j. In this example, the participant reported working with one IFRF source (ultrasound diathermy) and two RF sources (pulsed short-wave diathermy and continuous short-wave diathermy). Then, rate_d was divided by 1 or 2 accordingly. The number of years spent with each source reported in job j and occupational module m (duration[j,m]) was calculated on the basis of the starting and stopping dates working or in proximity of the reported RF or IF sources, taking into account the total number of years in job j where the participant declared not working with or in proximity of these sources (duration[j,m] = stopyear[j,m] – startyear[j,m] – notworking years[j,m]). The total duration of work in job j (duration[j]) was computed using the reported job's start and stop dates and should, therefore, be equal to or greater than the value for duration[j,m]. In the example, the start and stop dates in the occupational module were 1986 and 2000 and there was no year where the participant was not exposed to the sources reported. Thus, duration[j,m] = duration[j] = 14 years.

Other exposure determinants

Additional data which could modify the worker's exposure likelihood and level were also recorded. These modifying factors differ by occupational module (depending on whether exposure occurred in the near- and/or the far-field) and included various determinants related to how tasks were performed (e.g. in the industrial heating module exposure occurs mostly in the near-field and information was collected on whether the task was automated, done manually, or both, and if distance to the source was smaller or greater than 0.5 m). For sources that may lead to both near- and far-field exposures (i.e. radars and telecommunication antennas), more detailed information on distance (in meters or kilometers) was collected and used to estimate the worker's mean exposure.

Combination of exposure data by ISCO88 occupations

Time-weighted average estimates by ISCO88 code and frequency band

On the basis of the exposure indices (i.e. ICNIRP ratios or squared ratios) assigned to the reported source(s), the proportion of time that RF/IF exposure occurred during a typical work shift and other reported source-based ancillary information were used to obtain time-weighted average (TWA) exposure levels for each exposed ISCO88 code, by combining individual estimates from all subjects with the same code. Estimates of the arithmetic and geometric means, and their corresponding standard deviations (SD and GSD), were calculated for both E- and H-fields in the IFELF (equation 3), and IFRF and RF (equation 4) bands.

$$[\text{TWA} \quad \text{ICNIRP}_G \quad \text{ratio}[j,f]] \approx \frac{\begin{array}{c}\sum_m \text{duration}\ [j,m] \times \frac{Rate\ [j,m]}{S\ [j,m]} \\ \times \sum_{s=1}^{s_m} [\text{ICNIRP}_{G_{s[j,m]}}[f]]\,[f] \\ \times D\,[j,m] \times M\,[j,s,m]\end{array}}{\text{duration}\ [j]}, \tag{3}$$

$$[\text{TWA ICNIRP}_G \text{ squared ratio } [j,f]] \approx \frac{\sum_m \text{duration } [j,m] \times \frac{Rate\ [j,m]}{S\ [j,m]} \times \sum_{s=1}^{s_m} [\text{ICNIRP}_{G_{s[j,m]}}[f]]^2 [f] \times D\,[j,m] \times M[j,s,m]}{\text{duration } [j]}, \tag{4}$$

where $D[j,m]$ is a distance modifying factor in job j and module m, and $M[j,s,m]$ refers to other modifying factors applied to source s in job j, and module m. Since Rate was provided by job rather than by source, the number of hours of exposure is equally divided by the total number of sources ($S[j,m]$).

To avoid underestimation of exposure in jobs for which strict assumptions were used (e.g. exposure to sources in automated mode or at a distance greater than 0.5 m was considered negligible), an occupational background level (the lowest value in the JEM by field and frequency band) was assigned to these jobs. Only the ISCO88 codes for which subjects with this code did not report working with/nearby an RF or IF source were considered unexposed.

Probability of exposure by occupation and frequency band

Estimates of exposure probability (or proportion of exposed workers, above background) for each ISCO88 code were calculated as the number of exposed subjects, on the basis of the RF and/or IF sources reported, over the total number of subjects in each job title. ISCO88 codes not identified in INTEROCC as exposed as well as jobs with only background exposure level were assigned a 0% prevalence.

Methods for dealing with missing exposure data

Several ISCO88 codes not identified in the INTEROCC data were included in the JEM to maximize the utility of available data and cover as much of the ISCO88 classification system as possible. Estimates of exposure level (L) and probability (P) were inferred from nearest codes in the ISCO88 hierarchy, under the condition that the total number of exposed subjects in the nearest codes was ≥5.

JEM structure and content

The completed JEM was constructed using Microsoft Access©, which reduces the risk of accidental mass deletion/editing of data. The file includes axes for (i) ISCO88 codes, (ii) ISCO88 code description, (iii) number of INTEROCC subjects in the job code, (iv) number of INTEROCC subjects considered to be exposed above background in the job, (v) probability of exposure to E-fields (P_E), (vi) arithmetic mean (AM) of the TWA exposure as (squared) ICNIRP ratio for E-fields (AM TWA ICNIRP_E), standard deviation of the AM TWA ICNIRP_E (SD TWA ICNIRP_E), (vii) geometric mean (GM) of the TWA exposure as (squared) ICNIRP ratio for E-fields (GM TWA ICNIRP_E), geometric standard deviation of the GM TWA ICNIRP_E (GSD ICNIRP_E), (viii) probability of exposure to H-fields (P_H), (ix) AM TWA ICNIRP_H, SD TWA ICNIRP_H, and (x) GM TWA ICNIRP_H, GSD TWA ICNIRP_H, both as raw data and, where appropriate, as inferred estimates for all of the above.

Results

Job codes

The INTEROCC population used to construct the JEM comprises 9316 subjects, including 40.8% of cases and 59.2% of population-based controls. There were fewer male participants (45%) than female (55%), 24.5% were from Germany, 21.8% from Israel, 20.7% from UK, 12.8% from Australia, and less than 10% from Canada, France, and New Zealand (Table 1). A total of 36 011 job histories were recorded, which corresponded to 418 ISCO88 codes, including five non-occupational codes for unemployed/ill, pensioner, housewife/man, students, and prisoners. A total of 50 ISCO88 codes non-identified in INTEROCC were subsequently added in the JEM (see Supplementary Table S3, available at *Annals of Occupational Hygiene* online). Among the 468 ISCO88 codes finally present in the JEM, 83.2% are four-digit codes, 11.2% are three-digit codes, and 5.6% are two-digit codes. In total, 14 four-digit ISCO88 codes were not included in the JEM because of lack of information in INTEROCC and the inability to infer from close

Table 1. Characteristics of participants in INTEROCC study, 2000–2004, Australia, Canada, France, Germany, Israel, New Zealand, and the UK

INTEROCC population, N = 9316	n	%
Case/control status		
Cases	3803	40.8
Controls	5513	59.2
Sex		
Male	4196	45.0
Female	5120	55.0
Country		
France	710	7.6
Germany	2279	24.5
Israel	2029	21.8
UK	1927	20.7
Australia	1195	12.8
Canada	916	9.8
New Zealand	260	2.8

codes due to few exposed subjects (see Supplementary Table S4, available at *Annals of Occupational Hygiene* online).

Exposure data

Job codes

Of the 468 codes in the JEM, 179 were considered not exposed to RF, IFRF, or IFELF (i.e. probability = 0% and TWA ICNIRP ratio or squared ICNIRP ratio = 0). The remaining 289 codes were assigned exposure data (level and probability) for at least one of the three frequency bands, including 282 exposed to E-fields and 275 to H-fields. Most codes are exposed only to RF (87.9% for E-fields and 86.9% for H-fields), although some are exposed simultaneously in various frequency bands (Table 2).

Probability and level of exposure

Both the probability (*P*) and level (*L*) data in the three frequency bands are approximately log-normally distributed for both E- and H-fields. In the IFRF and IFELF bands, >90% of the jobs had a null probability, and among the exposed jobs above the background, the median was <2%, with a maximum of 14.3% (Fig. 1). In the RF band, 40% of the jobs had a null probability, whereas 30% had a probability between 0.3 and 5%. Among the exposed categories, the median probability was 5.1% for E-fields and 4.8% for H-fields (Fig. 1).

As shown in Table 3, the occupations (four-digit ISCO88 codes) with the highest probability of exposure to RF were 'Ships' deck officers and pilots' for E-fields (65%) (who declared working with the sources 'navigation radar', 'telecommunication antenna', and 'walkie-talkie') and 'Prison guards' for H-fields (61.9%) (who declared working with the sources 'two-way radio' and 'walkie-talkie'). The other occupations with high probability of exposure to RF E-fields (≥40%) were dominated by those of the maritime and aerial industries. For H-fields, they were dominated by those of the security sector.

The distribution of the TWA ICNIRP ratios or squared ratios for E- and H-fields is shown in Fig. 2 for the three frequency bands. For E-fields, there is a pattern of higher exposure levels in higher frequency bands. In the RF band, the values of the TWA ICNIRP ratios or squared ratios across the jobs exposed above the background range from 6.94×10^{-11} to 34.0 with a median of 0.61. In the IFRF band, exposure values were lower and ranged from 6.97×10^{-5} to 2.28, with a median of 0.042. In the IFELF band, the exposure values were low and all below the unity. For H-fields, exposure values are lower than those for E-fields, especially, for the RF frequency band where they were mostly (90%) below the unity with a 90th percentile of 1.1 and a maximum of 12.7. In the IFRF band, the values were very dispersed since they range between 7.5×10^{-12} and 4.7, with a median at 0.15. In the IFELF band, the values were much lower than the unity.

The four-digit occupational categories with the highest exposure level for E-fields (i.e. above the 90th percentile) are shown in Table 4. In the RF range, they were dominated by occupations using professional communication devices (e.g. walkie-talkies) and those using industrial heating sources (e.g. sealers, welders, dielectric heaters) and were linked, mostly (86%), to a low probability of exposure (<10%). For H-fields, the four-digit occupational

Table 2. Number of job categories in the JEM and number of job categories with exposure values by frequency ranges

	Job codes with exposure values			
	E-fields		H-fields	
	N	Frequency (%)	*N*	Frequency (%)
Only RF[a]	248	87.9	239	86.9
Only IFRF[b]	0	0.0	0	0.0
Only IFELF[c]	0	0.0	4	1.4
RF + IFRF	22	7.8	15	5.5
IFRF + IFELF	0	0.0	1	0.4
RF + IFELF	0	0.0	2	0.7
RF + IFRF + IFELF	12	4.3	14	5.1
Any	282	100.0	275	100.0

[a]RF, radiofrequency (>10 MHz) frequency band.
[b]IFRF, thermal intermediate frequency (100 kHz–10 MHz) frequency band.
[c]IFELF, non-thermal IF (3–100 kHz) frequency band.

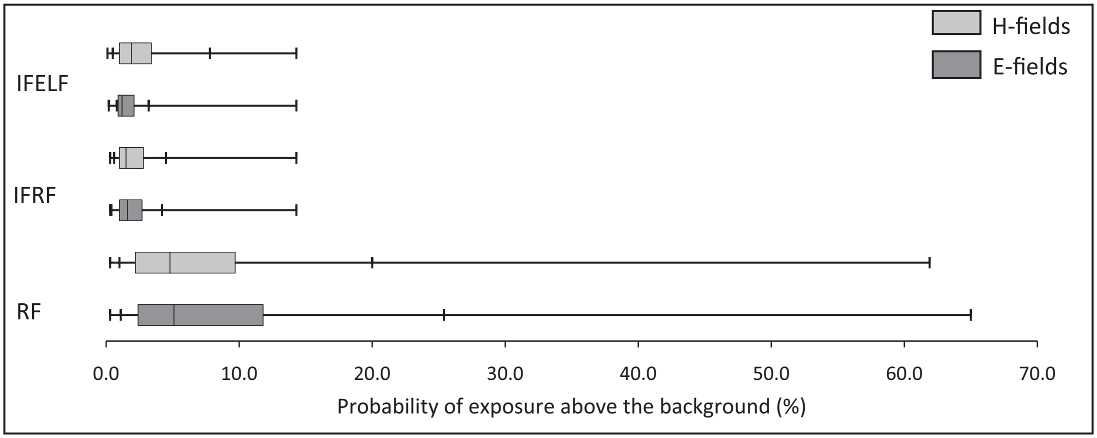

Figure 1. Distribution of the probability of exposure above background in the RF-JEM (minimum, 10th percentile, first quartile, median, third quartile, 90th percentile and maximum) for E- and H-fields and for RF, IFRF, and IFELF frequency bands, calculated on the basis of the source-exposure matrix and INTEROCC data.

Table 3. Occupations with the highest probability (>30%) of exposure to E- or H-fields (RF exposure)

ISCO88	ISCO88 label	Total number of subjects (*N*)	Number of exposed subjects (*n*)	Probability (%)
E-field				
3142	Ships' deck officers and pilots	20	13	65.0
5163	Prison guards	21	13	61.9
7112	Shotfirers and blasters	2	1	50.0
5162	Police officers	141	66	46.8
3144	Air traffic controllers	18	8	44.4
6153	Deep-sea fishery workers	7	3	42.9
7216	Underwater workers	5	2	40.0
8113	Well drillers and borers and related workers	5	2	40.0
H-field				
5163	Prison guards	21	13	61.9
7112	Shotfirers and blasters	2	1	50.0
8113	Well drillers and borers and related workers	5	2	40.0
5162	Police officers	141	56	39.7
3151	Building and fire inspectors	8	3	37.5
5169	Protective services workers not elsewhere classified	162	55	33.9
6151	Aquatic-life cultivation workers	6	2	33.3
5161	Fire-fighters	26	8	30.8

categories most highly exposed (above the 90th percentile) are presented in Table 5. In the RF band, they are largely dominated by those using industrial heating sources and the majority (55%) were also the occupations with the highest exposure to RF E-fields. Overall, these occupations were associated with higher probabilities than for E-fields.

Discussion

We have described the methods and content of, to our knowledge, the first comprehensive JEM specific to high-frequency EMF available in the literature. This JEM can be used to assess high-frequency EMF exposure in epidemiological studies as well as in occupational hygiene programs (Florentin *et al.*, 2017). The JEM was built by combining occupational data collected in a large population-based case–control study and source-based measurements extracted from the literature (Vila *et al.*, 2016) to provide estimates of probability and level of exposure to RF and IF EMF using the international ISCO88 coding system. The large sample size of the INTEROCC study (almost 10 000 subjects and over

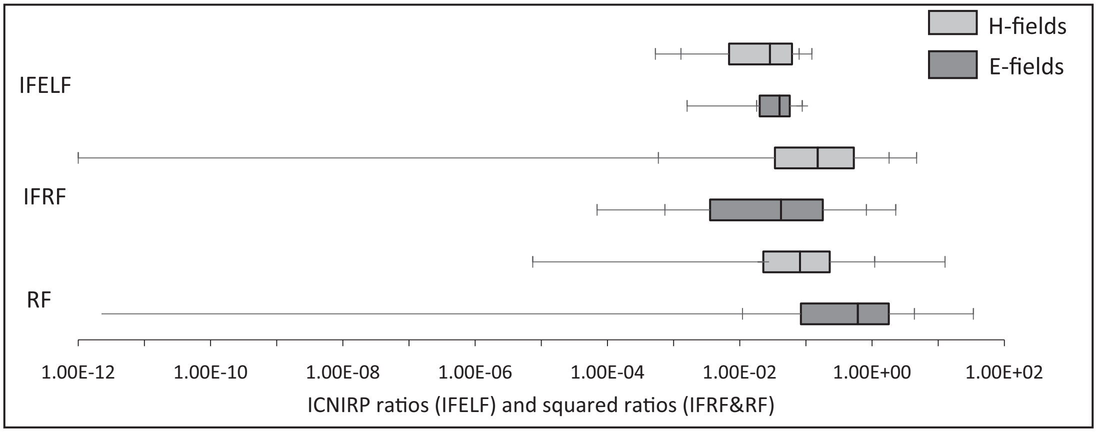

Figure 2. Distribution of the TWA ICNIRP ratios or squared ratios for exposures above background for each ISCO88 occupation in the RF-JEM (minimum, 10th percentile, first quartile, median, third quartile, 90th percentile and maximum) for E- and H-fields and for RF, IFRF, and IFELF frequency bands calculated on the basis of the source-exposure matrix and INTEROCC data.

35 000 jobs) allowed to include in the JEM exposure data for 468 ISCO88 (four-digit) codes, of which 62% are exposed to IFELF, IFRF, or RF.

This JEM, as well as the SEM used to construct it (Vila *et al.*, 2017), is based on measurements extracted from international literature resources (over 3000 measurements obtained in 15 countries) and from individual data collected in the seven countries of the multinational INTEROCC study (see Supplementary Table S5, available at *Annals of Occupational Hygiene* online, on available data by country). Therefore, since the JEM was mostly developed with data collected from developed countries, its representativity and potential worldwide applicability is debatable. Nevertheless, the validity of the JEM for use in a specific country will depend on the similarities of job practices and sources with the countries represented in the JEM (Röösli and Vienneau, 2014). Although most INTEROCC participants were aged from 30 to 59 years, which may not be representative of the general working population, some countries (Germany and UK) included subjects up to 69 years, while others (Israel and UK) recruited subjects from ≥18 years. This may reduce potential biases in the exposure estimation for younger and older workers, due to differences in work practices. Although the original proportion of men and women in INTEROCC were similar (45 and 55%, respectively), only 20% of exposed subjects were women, of which most of them reported the use of transmitters (45%), followed by food heating equipment (28%). This potential limitation may also represent real-life differences of occupations and/or tasks between men and women (Eng *et al.*, 2011).

The representativeness of this JEM for a given study population may also depend on the temporal variations in exposure, particularly important when considering high-frequency EMF due to the introduction of new technologies over the past 30 years (Frei *et al.*, 2009). The RF-JEM we have constructed is based on information collected between 2000 and 2004 from study participants, involving occupations since the 1970s and EMF measurements obtained between 1974 and 2013 (Vila *et al.*, 2016). Thus, it is possible that exposure levels associated with certain occupations may have changed over time (e.g. a roofer was not exposed to mobile phone base stations 30 years ago). This JEM will, therefore, need to be updated with newer data, when they become available, to be able to adapt its estimates to these changes and potential reductions of exposure levels associated with some EMF sources (Kelsh *et al.*, 2011; Vila *et al.*, 2017). To date, given the limited availability of measurements for some EMF sources, a time dimension was not included in the SEM or the JEM. Future improvements and additional data may allow creating indicators for different time periods.

The quality of the data in the JEM is related to the quality of the data in the underlying SEM, which was used to assign exposure estimates (E- and/or H-field levels) to the EMF sources reported in each job. The measurements used to construct the SEM came from different measurement campaigns, including different measurement parameters. Moreover, even for occupations with available data for both electric and magnetic fields, these estimates may refer to a combination of near- and far-field exposure scenarios (e.g. exposure to walkie-talkie and radar), so the physical relationships between E- and H-fields in free space under plane-wave

Table 4. Occupations belonging to the 10% of occupations with the highest E-field exposure levels (TWA ICNIRP ratios or squared ratios) by frequency band

ISCO88	ISCO88 label	Total number of subjects (*N*)	Number of exposed subjects (*n*)	Probability (%)	TWA ICNIRP ratio or squared ratio
RF[a]					
1228	Production and operations department managers in personal care, cleaning, and related services	16	6	6.3	7.5
1316	General managers in transport, storage, and communications	24	6	16.7	6.1
2221	Medical doctors	271	3	0.7	6.8
2455	Film, stage, and related actors and directors	25	3	12.0	10.1
3112	Civil engineering technicians	34	1	2.9	20.7
3115	Mechanical engineering technicians	73	3	8.2	6.8
3152	Safety, health, and quality inspectors	230	2	4.2	4.4
3413	Estate agents	87	3	6.9	5.8
4132	Production clerks	54	1	1.9	30.2
4221	Travel agency and related clerks	81	10	7.4	4.4
5121	Housekeepers and related workers	70	1	1.4	7.2
7121	Builders, traditional materials	55	2	3.6	13.7
7122	Bricklayers and stonemasons	92	4	3.3	5.9
7131	Roofers	27	1	3.7	13.1
7232	Aircraft engine mechanics and fitters	35	2	8.6	6.8
7245	Electrical line installers, repairers, and cable jointers	35	1	8.6	6.9
7341	Compositors, typesetters, and related workers	99	1	3.0	28.3
8232	Plastic-products machine operators	94	3	3.2	10.6
8253	Paper-products machine operators	15	6	13.3	5.7
8266	Shoemaking and related machine operators	20	3	5.0	28.3
8269	Textile, fur, and leather product machine operators not elsewhere classified	8	1	12.5	34.0
8281	Mechanical-machinery assemblers	52	2	3.8	4.5
8290	Other machine operators and assemblers	72	1	8.3	8.2
9312	Construction and maintenance laborers: roads, dams, and similar constructions	87	7	8.0	10.6
IFRF[b]					
3115	Mechanical engineering technicians	73	2	2.7	2.3
7212	Welders and flame cutters	209	7	3.3	0.8
7311	Precision-instrument makers and repairers	42	1	2.4	1.2
IFELF[c]					
7213	Sheet metal workers	102	1	1.0	0.1
8211	Machine-tool operators	120	1	0.8	0.1

[a]RF, radiofrequency (>10 MHz) frequency band.
[b]IFRF, thermal intermediate frequency (100 kHz–10 MHz) frequency band.
[c]IFELF, non-thermal IF (3–100 kHz) frequency band.

Table 5. Occupations belonging to the 10% of occupations with the highest H-field exposure levels (TWA ICNIRP ratios or squared ratios) by frequency band

ISCO88	ISCO88 label	Total number of subjects (*N*)	Number of exposed subjects (*n*)	Probability (%)	TWA ICNIRP ratio or squared ratio
RF[a]					
2221	Medical doctors	271	2	0.7	6.2
3115	Mechanical engineering technicians	73	6	6.8	6.9
3152	Safety, health, and quality inspectors	230	10	4.3	1.4
3211	Life science technicians	131	5	3.8	1.6
3226	Physiotherapists and related associate professionals	78	16	20.5	2.6
3416	Buyers	114	2	1.7	3.4
4122	Statistical and finance clerks	250	1	0.4	1.2
4132	Production clerks	54	1	1.8	11.6
7212	Welders and flame cutters	209	8	3.8	7.8
7213	Sheet metal workers	102	8	6.9	6.0
7242	Electronics fitters	63	10	15.9	1.2
7341	Compositors, typesetters, and related workers	99	3	3.0	9.5
8211	Machine-tool operators	120	1	0.8	12.7
8232	Plastic product machine operators	94	3	3.2	7.7
8253	Paper product machine operators	15	2	13.3	1.3
8266	Shoemaking and related machine operators	20	1	5.0	9.5
8269	Textile, fur, and leather product machine operators not elsewhere classified	8	1	12.5	11.4
8281	Mechanical-machinery assemblers	52	2	3.8	1.2
8290	Other machine operators and assemblers	72	6	8.3	3.1
9311	Mining and quarrying laborers	7	1	14.3	6.3
IFRF[b]					
3115	Mechanical engineering technicians	73	2	2.7	4.7
7212	Welders and flame cutters	209	7	3.3	2.0
7311	Precision-instrument makers and repairers	42	1	2.4	2.0
IFELF[c]					
8283	Metal finishing-, plating-, and coating-machine operators	23	2	8.7	0.12
7311	Shoe-makers and related workers	29	2	6.9	0.08

[a]RF, radiofrequency (>10 MHz) frequency band.
[b]IFRF, thermal intermediate frequency (100 kHz–10 MHz) frequency band.
[c]IFELF, non-thermal IF (3–100 kHz) frequency band.

(far-field) conditions (i.e. $E/H \approx 377$) may not always be present.

Another factor related to the use of the SEM data refers to the impact of using confidence-weighted exposure estimates from this database. Thus, to assess the quality and relevance of the measurement data used to construct the SEM, expert confidence ratings were used as weights to obtain confidence-weighted mean estimates (Vila *et al.*, 2017). Since the aim in INTEROCC was the analysis of brain tumor risk, one of the factors assessed by the experts was 'anatomical location', so measurements made at head level were upweighted in the calculation of the SEM estimates. To construct the current RF-JEM, confidence-weighted exposure estimates were used from the SEM. However, to improve the validity of the JEM for use in other studies and/or organs, exposure estimates using the unweighted exposure estimates from the SEM will be added to the JEM. Thus, the publicly available matrix will contain both types of estimates, so users can decide which values are more appropriate for their study.

Estimates of exposure level in the RF-JEM for each ISCO88 code are provided in the form of TWA ICNIRP ratios (in the IFELF band) and squared ratios (in the IFRF and RF bands), by combining the ratios or squared ratios of the sources reported by study subjects in each job. The use of ICNIRP-based metrics in the JEM allowed us to combine exposures from different frequency sources within our pre-defined IFELF, IFRF, and RF bands (e.g. RF sources may have frequencies in the kHz, MHz, and/or GHz ranges). This approach also allows the comparison (validation) of the estimates in the JEM with actual measurements by occupation since most current RF personal monitors for occupational exposure provide data as percentage of standards (reference levels) such as those issued by ICNIRP. The ratio for each EMF source was obtained by dividing the source's mean exposure value from the SEM by the corresponding frequency-dependent ICNIRP reference level. Mean exposure values for each RF or IF source from the SEM represent our best estimates of the mean exposure to EMF from a given source using available measurements from various exposure scenarios and equipment. Although some sources commonly operate at a single frequency, equipment using several frequencies may be encountered in occupational settings. For example, plastic sealers usually operate at 27 MHz, although sealers operating between 6 and 38 MHz may also be found (Conover *et al.*, 1980). In INTEROCC, information on the specific frequency used by each reported source is not available. Therefore, measurements for sources operating in a range of frequencies were collected, and mean exposure estimates were calculated in the SEM (Vila *et al.*, 2017). This information was considered when calculating ICNIRP ratios and squared ratios, as explained in Supplementary Material, Part A (available at *Annals of Occupational Hygiene* online).

Different EMF sources and tasks may lead to different exposure scenarios, involving localized (e.g. talking on a walkie-talkie) or whole-body (e.g. operating a glue dryer) exposure. Although this was not specifically considered in the methods to obtain our exposure estimates, the type and size of source, and the task(s) associated with it, are embedded within each source-occupation combination (e.g. soldier talking on walkie-talkie). The exposure from each source was further refined using additional available information (e.g. distance, portability). Moreover, additional source-based information available used to refine the assigned exposure level differ by occupational module (e.g. radars and telecommunication antennas may lead to whole-body exposure while exposure from portable transmitters was more likely to be localized). All this information helped assigning realistic individual estimates of exposure to study subjects which were then combined by occupational code to construct the JEM. Furthermore, the occupational module information is intrinsic within the ISCO88 code and is not needed to apply the JEM.

Possibly, the most important limitation of the RF-JEM is the small number of observations (i.e. exposed subjects within an occupation) available for some ISCO88 codes. Despite the large INTEROCC population, probability and level of exposure estimates were calculated with data from less than five exposed subjects in 70.4 and 73.0% of the ISCO88 codes, for E-fields and H-fields respectively. However, to provide more precise data, codes containing five or more records were used to infer exposure estimates (i.e. P and L) for codes without available or reliable data. This threshold value was considered a reasonable limit to minimize uncertainty (Bell, 1999). For these codes, both the raw and inferred estimates are available in the JEM, allowing future JEM users to select the more appropriate data and perform sensitivity analyses.

Although JEMs are useful tools to assess occupational exposure when individual measurements are not available, exposure estimates in the JEM refer to average levels of the entire group (i.e. occupation) and do not represent the exposure of each individual worker separately (Vergara *et al.*, 2012; Fischer *et al.*, 2017). Thus, the use of a JEM introduces Berkson error in the exposure estimate for a given subject. This type of error arises whenever group-mean exposures are assigned to individual workers since between- and within-worker exposure variability in each occupation can be large (Kromhout *et al.*, 1993). Although Berkson errors do not lead to substantial bias in risk estimates, they reduce statistical power to detect real associations (Armstrong, 1998). The availability of measures of exposure variability in the JEM (i.e. SD and GSD) may help to understand the inherent variability within each occupation. This information can also be used to correct risk estimates with bias attributable to Berkson error and to perform uncertainty propagation analysis (Jurek *et al.*, 2006; Greenland *et al.*, 2016).

It has been suggested that combining job title with work environment would improve exposure precision (Kelsh *et al.*, 2000). In our study, tasks and work environment were related to the type of EMF source(s) reported and the frequency of exposure. Since these exposure determinants were already considered in the calculation of the TWA estimates, we expect that these estimates reflect the most likely situations in each job. The availability of estimates of probability of exposure in the RF-JEM allows to reduce the impact of aggregating exposure data, which may vary within jobs across workplaces and even industries. Several methods have been proposed to use these data in combination with exposure intensity. Although the traditional approach has been to multiply P and L, this approach may introduce bias in the risk estimates (Burstyn *et al.*, 2012). Therefore, other methods are advisable, such as focusing on codes with both high exposure prevalence and intensity (Burstyn *et al.*, 2012).

EMF exposure > 100 kHz leads to significant energy absorption (ICNIRP, 1998), and energy, or power density (S), is proportional to squared field strength (i.e. $S = E^2/377 = 377H^2$, in the far-field). Therefore, to develop exposure indices above 100 kHz both the source's mean exposure and its corresponding reference level were squared. We assumed that ICNIRP ratios should be proportional to internal electric fields, while squared ratios should correlate well with SAR. SAR is a metric traditionally associated with thermal effects (ICNIRP, 1998). However, SAR is also proportional to the square of the internal electric field strength. Thus, SAR = $\sigma E_i^2/\rho$, where σ denotes the effective conductivity of the tissue and E_i is the internal (induced) electric field distributed over a mass density (ρ) (Hansson Mild and Mattsson, 2017). Therefore, if biological and health effects other than those induced by heat exist, both SAR (i.e. the RF dose rate) and RF dose (specific absorption, SA, in J/kg) should also correlate with potential non-thermal effects. We considered the possibility of using SAR and E_i estimates in the JEM, based on the ICNIRP ratios or squared ratios and the corresponding frequency-dependent basic restrictions (see Supplementary Material, Part B, available at *Annals of Occupational Hygiene* online). However, since internal (dose) levels are more difficult to validate/update, we decided against using these metrics in this first JEM.

Although other occupational exposure limits for EMF exist (NRPB, 2004; IEEE, 2005), the ICNIRP RLs were chosen to standardize our data since they are internationally recognized, are issued in collaboration with the WHO, and are the basis for the limits established in Europe (EU, 2013). However, like other safety standards, ICNIRP RLs may change over time, which may require updating the values in the JEM. In this regard, ICNIRP is currently reviewing their guidelines above 100 kHz. However, changes in the reference levels, if they occur, are likely to be small (Croft, 2018). The use of ICNIRP-based exposure metrics has other limitations. ICNIRP RLs used to obtain the ratios and squared ratios are issued for compliance purposes to protect workers from short-term well-known health effects, and their validity for use in epidemiological studies is unknown. Moreover, since the use of ICNIRP ratios (or squared ratios) in epidemiological studies assume that the potential health effects may be associated with the mechanisms used to derive the RLs (i.e. heating and electrostimulation), improved methods to combine exposures from different frequency sources need to be developed in the future. We have proposed improvements including dose estimates, such as SAR and induced fields, using the relationships between RLs and BRs, as well as adding further frequency bands to allow calculating frequency-unweighted exposure estimates. We expect that the methods proposed in this study will contribute to this difficult task, building upon previous efforts toward better integrative and cumulative exposure/dose EMF assessment (Baste *et al.*, 2010; Hansson Mild and Mattsson, 2017).

ICNIRP ratios or squared ratios in the JEM may be >1 in some occupations, which represents an overexposure situation since these values are obtained by comparing with the corresponding frequency-dependent occupational exposure limits (i.e. reference levels). Some studies have shown that workers performing maintenance tasks on telecommunication antennas (Hansson Mild, 1981) or operators of plastic welding machines (Eriksson and Hansson Mild, 1985) may substantially exceed occupational standards. For example, workers exposed to highly localized near-fields such as those from walkie-talkies are likely to be in noncompliance when compared with RLs since comparisons with safety standards for these sources require comparison with SAR (Mantiply *et al.*, 1997; ICNIRP, 1998). Although the information provided by the comparison with safety standards was not the main aim of using ICNIRP reference levels, and despite the limitations described above, it may be useful to identify the occupations most likely at risk.

When applying the JEM in an epidemiological study to assess long-term health effects, indices of cumulative exposure may be calculated using the JEM's mean estimates and available information on exposure duration (e.g. in years). Thus, since ICNIRP squared ratios are assumed to correlate well with SAR, ratios over time should correlate well with the RF dose (SA), which has been recently proposed as a potentially useful metric for RF risk analysis (Hansson Mild *et al.*, 2005; Hansson Mild and Mattsson, 2017). Nevertheless, since epidemiological studies may prefer the use of exposure metrics not associated with any particular biophysical mechanism, future versions of the JEM may include dose estimates as well as frequency-unweighted exposure estimates (e.g. with units V/m, A/m, and/or W/m^2) by, for example, adding further frequency bands to the JEM, so different frequency exposures can be combined without the need of frequency weighting.

To construct this JEM, we used all available data from the INTEROCC case–control study. Several arguments are in favor of excluding the information from cases when building a JEM (Peters *et al.*, 2011). In particular, since INTEROCC cases were selected to study brain cancer risk, if there is an association between exposure to RF or IF EMF and the brain tumors studied, cases would have likely been more highly exposed than controls and the JEM estimates could be biased toward higher exposures. However, in a recent case–control study of lung cancer (Kirkham *et al.*, 2016), differences between JEMs from case-only data and control-only data were found to be small, concluding that it is justifiable, and valuable, to combine data from cases and controls when creating a JEM. Moreover, although the proportion of exposed cases in our study population (37%) is smaller than that of exposed controls (63%), a comparison between a controls-only JEM and a JEM using data from all exposed subjects did not find significant differences (data not shown). Moreover, our decision to construct the RF-JEM using all available data was also reinforced by the small number of exposed subjects available for many codes.

In conclusion, we have constructed a comprehensive quantitative JEM, describing occupational exposure to high-frequency EMF using an international standardized coding system. Despite its limitations, this JEM may be used in epidemiological studies with information on occupational histories (and ideally EMF sources) of study subjects, as well as in occupational health management programs where the occupations most at risk need to be identified (Florentin *et al.*, 2017). As shown in Supplementary Table S4 (available at *Annals of Occupational Hygiene* online), only 14 (four-digit) jobs are missing from this JEM. Nevertheless, since numerous exposure estimates are currently based on few available observations, future efforts should be made to complement/calibrate this JEM. In particular, data from measurement campaigns which should ideally be performed in different countries would be valuable. Also, data from other case–control studies where information on RF sources are available could complete and update this JEM, improving the validity of its exposure estimates. The RF-JEM will be maintained and made publicly available at the ISGlobal website (http://radiation.isglobal.org/index.php/jp/databases) for use by other researchers.

Supplementary Data

Supplementary data are available at *Annals of Work Exposures and Health* online.

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Disclaimer

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Conflict of interest

The authors declare no conflicts of interest.

Ethics approval

Ethics approval was obtained from appropriate national and regional research ethics boards, including the Ethical Review Board of IARC (Lyon) for INTERPHONE and the Municipal Institute for Medical Investigation (IMIM) Barcelona for INTEROCC.

References

Ahlbom A, Kheifets L, Savitz D *et al*. (2004) Epidemiology of health effects of radiofrequency exposure. *Environ Health Perspect*; **112**: 1741–54.

Armstrong BG. (1998) Effect of measurement error on epidemiological studies of environmental and occupational exposures. *Occup Environ Med*; **55**: 651–6.

Baldi I, Coureau G, Jaffré A *et al*. (2011) Occupational and residential exposure to electromagnetic fields and risk of brain tumors in adults: a case–control study in Gironde, France. *Int J Cancer*; **129**: 1477–84.

Baste V, Hansson Mild K, Moen BE. (2010) Radiofrequency exposure on fast patrol boats in the Royal Norwegian Navy – an approach to a dose assessment. *Bioelectromagnetics*; **31**: 350–60.

Baste V, Moen BE, Oftedal G *et al*. (2012) Pregnancy outcomes after paternal radiofrequency field exposure aboard fast patrol boats. *J Occup Environ Med*; **54**: 431–8.

Baste V, Riise T, Moen BE. (2008) Radiofrequency electromagnetic fields; male infertility and sex ratio of offspring. *Eur J Epidemiol*; **23**: 369–77.

Bell S. (1999) *A beginner's guide to uncertainty of measurement*. Teddington, UK: National Physical Laboratory.

Berg G, Spallek J, Schüz J *et al*.; Interphone Study Group, Germany. (2006) Occupational exposure to radio frequency/microwave radiation and the risk of brain tumors: Interphone Study Group, Germany. *Am J Epidemiol*; **164**: 538–48.

Bortkiewicz A, Gadzicka E, Szymczak W *et al*. (2012) Heart rate variability (HRV) analysis in radio and TV broadcasting stations workers. *Int J Occup Med Environ Health*; **25: 446–55**. doi:10.2478/s13382-012-0059-x.

Burstyn I, Lavoué J, Van Tongeren M. (2012) Aggregation of exposure level and probability into a single metric in job-exposure matrices creates bias. *Ann Occup Hyg*; **56**: 1038–50.

Cardis E, Richardson L, Deltour I *et al*. (2007) The INTERPHONE study: design, epidemiological methods, and description of the study population. *Eur J Epidemiol*; **22**: 647–64.

Chen Q, Xu G, Lang L *et al*. (2013) ECG changes in factory workers exposed to 27.2 MHz radiofrequency radiation. *Bioelectromagnetics*; **34**: 285–90.

Conover DL, Murray WE, Foley ED *et al*. (1980) Measurements of electric- and magnetic-field strengths from industrial radio-frequency (6–38 MHz) plastic sealers. *Proc Inst Electr Electron Eng*; **68**: 17–20.

Croft. (2018) ICNIRP radiofrequency guidelines public consultation version. Available at https://www.icnirp.org/cms/upload/consultation_upload/ICNIRPCroft_PCD_BioEM2018.pdf. Accessed 10 August 2018.

Eng A, 't Mannetje A, McLean D *et al*. (2011) Gender differences in occupational exposure patterns. *Occup Environ Med*; **68**: 888–94.

Eriksson A, Hansson Mild K. (1985) Radiofrequency electromagnetic leakage fields from plastic welding machines. Measurements and reducing measures. *J Microw Power Electromagn Energy*; **20**: 95–107.

EU. (2013) *Directive 2013/35/EU of the European Parliament and the Council of 26 June 2013 on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (electromagnetic fields)*. pp. 1–21.

Fischer HJ, Vergara XP, Yost M *et al*. (2017) Developing a job-exposure matrix with exposure uncertainty from expert elicitation and data modeling. *J Expo Sci Environ Epidemiol*; **27**: 7.

Florentin A, Zmirou-Navier D, Paris C; Rnv3p Members. (2017) Contribution of job-exposure matrices for exposure assessment in Occupational Safety and Health Monitoring Systems: application from the French National Occupational Disease Surveillance and Prevention Network. *Int Arch Occup Environ Health*; **90**: 491–500.

Frei P, Mohler E, Neubauer G *et al*. 2009. Temporal and spatial variability of personal exposure to radio frequency electromagnetic fields. *Environ Res*; **109**: 779–85.

Garaj-Vrhovac V, Gajski G, Pažanin S *et al*. 2011. Assessment of cytogenetic damage and oxidative stress in personnel occupationally exposed to the pulsed microwave radiation of marine radar equipment. *Int J Hyg Environ Health*; **214**: 59–65.

Grayson JK. (1996) Radiation exposure, socioeconomic status, and brain tumor risk in the US Air Force: a nested case–control study. *Am J Epidemiol*; **143**: 480–6.

Greenland S, Fischer HJ, Kheifets L. (2016) Methods to explore uncertainty and bias introduced by job exposure matrices: methods to explore uncertainty from job exposure matrices. *Risk Anal*; **36**: 74–82.

Hansson Mild K. (1981) Radiofrequency electromagnetic fields in Swedish radiostations and tall FM/TV towers. *Bioelectromagnetics*; **2**: 61–9.

Hansson Mild K, Carlberg M, Wilén J *et al*. (2005) How to combine the use of different mobile and cordless telephones in epidemiological studies on brain tumours? *Eur J Cancer Prev*; **14**: 285–8.

Hansson Mild K, Mattsson MO. (2017) Dose and exposure in bioelectromagnetics. In Markov M, editor. *Dosimetry in bioelectromagnetics*. Boca Raton, FL: CRC Press. pp. 101–18.

Hareuveny R, Kavet R, Shachar A *et al*. (2015) Occupational exposures to radiofrequency fields: results of an Israeli national survey. *J Radiol Prot*; **35**: 429–45.

Hitchcock RT. (2004) *Radio-frequency and microwave radiation*. 3rd edn. Fairfax, VA: AIHA.

IARC. (2013) *IARC monographs. Non-ionizing radiation, part 2: radiofrequency electromagnetic fields*. Vol. **102**. Lyon, France: International Agency for Research on Cancer.

IARC Monographs Priorities Group. (2019) Advisory group recommendations on priorities for the IARC monographs. *Lancet Oncol*; **20**: 763–64.

ICNIRP. (1998) Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 300 GHz). *Health Phys*; **74**: 494–522.

ICNIRP. (2010) Guidelines for limiting exposure to time-varying electric and magnetic fields (1 Hz to 100 KHz). *Health Phys*; **99**: 818–36.

IEEE. (2005) *IEEE standard for safety levels with respect to human exposure to radiofrequency electromagnetic fields, 3 KHz to 300 GHz. C95.1*. New York, NY: IEEE.

International Telecommunications Union (ITU). (2008) Frequency and wavelength bands. Radio regulations. Available at http://www.itu.int/dms_pub/itu-s/. Accessed 12 April 2018.

Jurek AM, Maldonado G, Greenland S *et al*. (2006) Exposure-measurement error is frequently ignored when interpreting epidemiologic study results. *Eur J Epidemiol*; **21**: 871–6.

Karipidis K, Benke G, Sim MR. (2008) Feasibility of constructing the radiation component of an Australian job-exposure matrix. *J Occup Health Safety*; **24**: 53–62.

Kauppinen T, Toikkanen J, Pukkala E. (1998) From cross-tabulations to multipurpose exposure information systems: a new job-exposure matrix. *Am J Ind Med*; **33**: 409–17.

Kelsh MA, Kheifets L, Smith R. (2000) The impact of work environment, utility, and sampling design on occupational magnetic field exposure summaries. *AIHAJ*; **61**: 174–82.

Kelsh MA, Shum M, Sheppard AR *et al*. (2011) Measured radiofrequency exposure during various mobile-phone use scenarios. *J Expo Sci Environ Epidemiol*; **21**: 343–54.

Kirkham TL, Siemiatycki J, Labrèche F *et al*. (2016) Impact of aggregating exposure information from cases and controls when building a population-based job-exposure matrix from past expert evaluations. *Occup Environ Med*; **73**: 474–81.

Kromhout H. (2002) Commentary on Teschke *et al*., 2002 occupational exposure assessment in case–control studies: opportunities for improvement. *Occup Environ Med*; **59**: 575–94.

Kromhout H, Symanski E, Rappaport SM. (1993) A comprehensive evaluation of within- and between-worker components of occupational exposure to chemical agents. *Ann Occup Hyg*; **37**: 253–70.

Mantiply ED, Pohl KR, Poppell SW *et al*. (1997) Summary of measured radiofrequency electric and magnetic fields (10 KHz to 30 GHz) in the general and work environment. *Bioelectromagnetics*; **18**: 563–77.

Mjøen G, Sætre DO, Lie RT *et al*. (2006) Paternal occupational exposure to radiofrequency electromagnetic fields and risk of adverse pregnancy outcome. *Eur J Epidemiol*; **21**: 529–35.

Møllerløkken OJ, Moen BE. (2008) Is fertility reduced among men exposed to radiofrequency fields in the Norwegian Navy? *Bioelectromagnetics*; **29**: 345–52.

NRPB. (2004) *Review of the scientific evidence for limiting exposure to electromagnetic fields (0–300 GHz)*. Oxfordshire, UK: NRPB. pp. 3.

Peters S, Glass DC, Milne E *et al*.; Aus-ALL Consortium. (2014) Rule-based exposure assessment versus case-by-case expert assessment using the same information in a community-based study. *Occup Environ Med*; **71**: 215–9.

Peters S, Vermeulen R, Cassidy A *et al.*; INCO Group. (2011) Comparison of exposure assessment methods for occupational carcinogens in a multi-centre lung cancer case–control study. *Occup Environ Med*; **68**: 148–53.

Röösli, M, Vienneau D. (2014) *Epidemiology of electromagnetic fields*. Boca Raton, FL: Taylor & Francis group.

SCENIHR. (2015) Opinion on potential health effects of exposure to electromagnetic fields (EMF). *Bioelectromagnetics*; **36**: 480–84.

Singh S, Kapoor N. (2015) Occupational EMF exposure from radar at X and Ku frequency band and plasma catecholamine levels. *Bioelectromagnetics*; **36**: 444–50.

Singh S, Mani KV, Kapoor N. (2015) Effect of occupational EMF exposure from radar at two different frequency bands on plasma melatonin and serotonin levels. *Int J Radiat Biol*; **91**: 426–34.

Stang A, Anastassiou G, Ahrens W *et al*. (2001) The possible role of radiofrequency radiation in the development of uveal melanoma. *Epidemiology*; **12**: 7–12.

Szmigielski S. (1996) Cancer morbidity in subjects occupationally exposed to high frequency (radiofrequency and microwave) electromagnetic radiation. *Sci Total Environ*; **180**: 9–17.

Taskinen H, Kyyrönen P, Hemminki K. (1990) Effects of ultrasound, shortwaves, and physical exertion on pregnancy outcome in physiotherapists. *J Epidemiol Community Health*; **44**: 196–201.

Teschke K, Olshan AF, Daniels JL *et al*. (2002) Occupational exposure assessment in case–control studies: opportunities for improvement. *Occup Environ Med*; **59**: 575–93; discussion 594.

Vergara XP, Kheifets L, Silva M *et al*. (2012) New electric-shock job exposure matrix. *Am J Ind Med*; **55**: 232–40.

Vila J, Bowman JD, Figuerola J *et al*. (2017) Development of a source-exposure matrix for occupational exposure assessment of electromagnetic fields in the INTEROCC study. *J Expo Sci Environ Epidemiol*; **27**: 398–408.

Vila J, Bowman JD, Richardson L *et al*. (2016) A source-based measurement database for occupational exposure assessment of electromagnetic fields in the INTEROCC study: a literature review approach. *Ann Occup Hyg*; **60**: 184–204.

Wang Z, Wang L, Zheng S *et al*. (2016) Effects of electromagnetic fields on serum lipids in workers of a power plant. *Environ Sci Pollut Res Int*; **23**: 2495–504.

Wilén J, Hörnsten R, Sandström M *et al*. (2004) Electromagnetic field exposure and health among RF plastic sealer operators. *Bioelectromagnetics*; **25**: 5–15.

Wilén J, Wiklund U, Hörnsten R *et al*. (2007) Changes in heart rate variability among RF plastic sealer operators. *Bioelectromagnetics*; **28**: 76–9.