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Personal exposure to radiofrequency electromagnetic fields in various occupations in Spain and France

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ABSTRACT

Background: A preliminary job-exposure matrix (JEM) for radiofrequency electromagnetic fields (RF-EMF) was created based on self-reported occupational information from a multi-country population-based study of approximately 10,000 participants combined with available measurement data compiled in a source-exposure matrix (spot measurements). In order to address the limited personal occupational RF-EMF measurement data available in the literature, we performed a measurement campaign among workers in various occupations in Spain and France.

Methods: Personal full-shift measurements were conducted using RadMan 2XT™ (Narda) devices. A worker diary was used to capture information on occupational and background sources of RF exposure during the shift. Inclusion of occupations to be measured was initially based on exposure prevalence and level information in the preliminary JEM and expert judgment.

Results: Personal full-shift measurements were conducted among 333 workers representing 46 ISCO88 occupations. Exposure to electric (E) and magnetic (H) fields was infrequent with >99% of measurements below the detection limit of the device (≥1% of the 1998 ICNIRP standards). A total of 50.2% and 77.2% of workers were ever exposed to E and H fields respectively (having at least one recorded 1-second measurement above the detection limit). Workers in elementary occupations, technicians and associate professionals, plant and machine operators and assemblers had somewhat greater numbers of measurements above the detection limit, higher maximum values and longer exposure durations. A small proportion of measurements were ≥100% of the standards, though these exceedances were brief (generally a few seconds in duration). Female workers and workers reporting use of any RF-EMF emitting source were more likely to have a measured exposure to E and H fields.

Conclusion: We conducted personal RF-EMF measurements among workers in various occupations in Spain and France. Overall, RF-EMF exposure ≥1 % ICNIRP was infrequent, despite some intermittent exposures ≥100% observed among workers in some occupations.

1. Introduction

Interest in radiofrequency electromagnetic fields (RF-EMF) has developed since the late 19th century, but increased in the 1920s, with the development and democratization of radio and TV broadcasting (Foster et al., 2022). Since then, the number and variety of RF-EMF sources has been rising in the work environment. RF-EMF devices which can heat matter (i.e. diathermy) are used in the medical sector, including in rehabilitation, surgery, and other medical procedures (Andrikopoulos et al., 2017; De Marco and Maggi, 2006; Koutsojannis

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et al., 2018; Macca et al., 2007). RF-EMF are also used in MRI systems (Berlana and Úbeda, 2017; Gourzoulidis et al., 2015). In the industrial sector, numerous types of equipment using RF-EMF are commonly used to weld (Chen et al., 2013; Xu et al., 2016) and seal (Sirav et al., 2010) different types of materials, as well as to operate machining-tools remotely (Michalowska et al., 2018). In the telecommunications sector, RF-EMF are widely used in broadcasting (Azah et al., 2013; Alanko and Hietanen, 2007; Litchfield et al., 2017; Osei et al., 2016; Politański et al., 2018; Valic et al., 2012), mobile telephony (Alanko et al., 2008; Pascuzzi and Santoro, 2015) and air traffic communication (Joseph et al., 2012a, 2012b, 2012c). RF-EMF are also used for radars, for civilian or military purposes (Gallucci et al., 2022; Halgamuge, 2015; Paljanos et al., 2015; Sobiech et al., 2017).

With the overall increase of RF-EMF use in occupational environments, recommended exposure limits or guidelines were defined for workers in order to avoid adverse health effects such as burns and increased tissue temperature by ICNIRP (International Commission on Non-Ionizing Radiation Protection) (Ahlbom et al., 2004). These guidelines include basic restrictions, which are internal or dosimetric RF-EMF limits which are directly related to well-known adverse health effects, and reference levels which are derived from the basic restrictions and are more easily measured for compliance purposes. Adverse health effects associated with RF-EMF [3 kHz–300 GHz] include short-term effects such as electrostimulation below 10 MHz and tissue heating above 100 kHz. Studies of cancer due to long-term exposure to RF-EMF have been inconclusive and RF-EMF was classified as Group 2B (possibly carcinogenic) by the International Agency for Research on Cancer in 2011 (IARC, 2013). Numerous other potential acute and chronic health effects have been studied with varying results (Ahlbom et al., 2004) including cardiovascular effects (Chen et al., 2013), reproductive effects (Baste et al., 2012; Shah and Farrow, 2014; Xu et al., 2016), effects on the eyes and vision (Adibzadeh et al., 2016; Algaily et al., 2015), effects on the immune system (Piszczek et al., 2021), sleep quality (Liu et al., 2014; Tettamanti et al., 2020), and neurodevelopmental and behavioral effects (Bodewein et al., 2022).

Studies of occupational exposure to RF-EMF have relied on a range of exposure assessment approaches. Exposure assessment in most cases has been limited by the capabilities and types of exposure meters available for conducting measurements. Studies have often used fixed-site monitoring, spot measurements (Alanko et al., 2008; Alanko and Hietanen, 2007; Andrikopoulos et al., 2017; Azah et al., 2013; Barbiroli et al., 2011; Berlana and Úbeda, 2017; Chen et al., 2013; De Marco and Maggi, 2006; de Miguel-Bilbao et al., 2014; Di Nallo et al., 2008; Gourzoulidis et al., 2015; Halgamuge, 2015; Hamnerius, 2009; Helbet et al., 2018; Jomaa et al., 2017; Joseph et al., 2008, 2012c; Khan et al., 2018; Koutsi et al., 2019; Litchfield et al., 2017; Massardier-Pilonchery et al., 2019; Nedic et al., 2016; Osei et al., 2016; Paljanos et al., 2015; Pascuzzi and Santoro, 2015; Plets et al., 2016; Politański et al., 2018; Valic et al., 2012) or operator position measurements (Macca et al., 2007; Michalowska et al., 2018; Roivainen et al., 2014; Sirav et al., 2010; Sobiech et al., 2017; Xu et al., 2016; Zubrzak et al., 2017). While these methods are relatively simple, inexpensive, and do not require extensive cooperation from study participants, they may not fully reflect exposure patterns experienced by workers as they perform their daily tasks, and there may be variation in spatial and temporal exposures on a personal scale (Röösli et al., 2010). More recently, some studies have assessed occupational exposure to RF-EMF using personal meters that can be worn by the study participant during their daily activities (Litchfield et al., 2016; Massardier-Pilonchery et al., 2019).

The INTEROCC population-based case-control study, which is a subset of the larger INTERPHONE study, obtained data from participants in seven of the thirteen participating countries (Australia, Canada, France, Germany, Israel, New Zealand, and the United Kingdom) (Cardis et al., 2007). As part of this study on occupational exposures and brain cancer risk (Vila et al., 2016), an Occupational Exposure Measurement Database (OEMD), combining EMF measurements and complementary data from the literature, was created including the most common sources of exposure to EMF in the workplace. Based on the OEMD, various metrics of exposure were calculated and summarized by source into a Source-Exposure Matrix (SEM) (Vila et al., 2017). Occupational data included information about the participants' occupational history, including job titles and start and stop dates of every job held for six months or longer. Based on the SEM and ancillary information from INTEROCC, a preliminary Job-Exposure Matrix (JEM) for RF-EMF was constructed by combining the detailed occupational questionnaire information, such as on tasks performed and EMF sources used, and other modifying factors (i.e. distance to source), collected from the nearly 10,000 case and control participants (Migault et al., 2019; Vila et al., 2017). The resulting JEM provided estimates of prevalence and level of RF-EMF exposure for 468 four-digit ISCO88 jobs for both electric (E) and magnetic (H) fields. The estimates of exposure were calculated using ICNIRP ratios (for frequencies $<$100 kHz) and ICNIRP squared ratios (for frequencies $>$100 kHz), which consider the frequency-dependent thresholds of biological responses (Migault et al., 2019). However, an important limitation of this preliminary RF-JEM is that exposure estimates were compiled from the OEMD and SEM databases which were drawn exclusively from available literature data from 1974 to 2013 and contain mainly source-based measurements and few personal measurements for RF sources (Vila et al., 2016). Exposure estimates were also calculated based on a small number of observations per ISCO code (Migault et al., 2019). As part of an international project, OccRF-Health, aimed at assessing this preliminary RF-JEM, we conducted the first stage of a data collection campaign of personal measurements of occupational RF-EMF exposure among workers in various occupations in Spain and France.

2. Methodology

2.1. Identification of occupations to be measured

The occupations to be measured in this study were initially identified based on RF exposure prevalence and level information from the preliminary RF-JEM and the ISCO88 classification of occupations. Jobs with 4-digit ISCO88 titles that were assumed to have medium ($\geq$50th percentile) and higher ($\geq$90th percentile) levels of exposure to RF-EMF were initially prioritized for measurements.

2.2. Participant and company selection

The study was promoted through various media, including contact with occupational hygienists, local or regional occupational health and safety departments, labour representatives, and personal contacts. Initial contact was made with representatives of potential participating companies to explain the study's objectives and measurement processes. In some instances, a preliminary onsite visit was conducted to identify potential sources of RF-EMF exposure. The measurements were conducted across various types of occupations within a company or workplace to gather exposure data for a broad range of occupations at each site. All measurements were collected between February 2021 and July 2022. The process of obtaining participation agreements from the companies was impacted by the COVID-19 pandemic during this period, with some sites requesting to delay their participation as a result of government measures and restrictions, as well as the sanitary protocols in place within their companies.

2.3. Measurement protocol and instrumentation

2.3.1. Measurement protocol

During the scheduled work shift, a trained investigator met with the participant(s) at the workplace, typically with the assistance of a manager or a delegated health and safety worker. The participants were informed about the study measurement protocol and an informed consent was obtained with a signed participation agreement. The personal exposure meter was attached to a harness worn outside the participant's clothing, positioned at the level of the left chest pocket. In cases of hospital occupations requiring patient manipulation, the meter was placed in the chest pocket of the uniform or at the waist level. The exposure meter was activated once the preparation and explanation phase were completed, and exposure was recorded at a sampling rate of 1 measurement/second until the end of the shift. After that, the device was switched off and removed from the participant, to whom the investigator administered an additional questionnaire (i.e. worker diary, see below).

2.3.2. Instrumentation

The selection of the RF measurement device for this study was based on considerations related to: 1) equipment weight, 2) practicality when worn during a full shift, 3) ability to measure both electric (E) and magnetic (H) fields independently, 4) available sampling rate, and 5) frequency and measurement range covered. The Radman 2XT™ (Narda Safety Test Solutions GmbH, Pfullingen, Germany) is a personal meter designed for hazard protection of occupational exposure to RF-EMF. It performs isotropic measurements of both E and H fields ≥1 % of the occupational standard in the frequency range of [900 kHz–60 GHz] and [27 MHz–1 GHz] reliably in both near and far field conditions (Narda safety test solutions, 2023a). Results are frequency-shaped, meaning that they are provided as the ratio of the exposure level measured for a specific frequency range and the corresponding standard reference level range. Thus, results are presented in percentages of the ICNIRP 1998 occupational standards, which stipulates reference levels for occupational exposure to RF–EMF with varying field strength across the RF–EMF spectrum (Fig. S1, *Supplementary Material)*. The sensitivity of the Radman 2XT™, or the threshold below which the reliability of the measured values is not guaranteed, is <1 % of the ICNIRP 1998 occupational standard (Narda safety test solutions, 2023b). Each unit was calibrated before the Spanish data collection and recalibrated before the measurements in France.

2.3.3. Worker diary

The worker diary was administered face-to-face and the data were captured on an electronic tablet at the end of the measurement day. In a few cases, paper versions were collected, and investigators then entered the data electronically using a double-entry method. The worker diary had three sections: 1) basic and personal information, including occupation and occupational sector, based on the INTEROCC study occupational questionnaire, and two new sections specific to digital platform and warehouse workers; 2) sources of exposure to RF-EMF used during the first and second half of the work shift, specific to the occupational sector; and 3) general information about the work shift, including the impact of COVID-19 on work organization, malfunction of RF sources used during the day, impact of the exposimeter on occupational tasks, and representativeness of the working day during which the sampling took place.

2.3.3.1. Occupational RF sources. Self-reported occupational RF sources used during the working day were captured and classified according to each occupational sector (see above). Questions were formulated as follows: 1) an exhaustive list of RF sources was provided per sector (both occupational and environmental sources such as Wi-Fi); and 2) typical distance of use/exposure of each RF source: hand-held/direct contact; ≤50 cm, >50 cm.

2.3.3.2. Mobile phone use. Questions about personal mobile phone use over the measured work shift were asked, for the first and second half of the shift. Questions focused first on the ON/OFF status of the personal mobile phone, and where it was generally kept during the shift. Then, information about the type of functions used were collected (phone calls, text messages, streaming, internet browsing etc.), as well as the estimated frequency and cumulative-time of use of each function.

2.4. Statistical analysis

Job titles captured in the "Worker-diary" were assessed by an occupational hygienist in relation to the type of company and occupational sector, sources used, and the main tasks performed over the day, and used to assign a four-digit ISCO88 job code. Descriptive analysis was performed to characterize sociodemographic characteristics of workers by ISCO88 job code. Analysis of worker measurement data for both E and H fields included the proportion of exposed workers (based on having any recorded measurement ≥1% of the ICNIRP 1998 occupational standards captured over the work shift), the proportion of measurements ≥1% of the ICNIRP 1998 occupational standards during a work shift (as well as of ≥100%), and the geometric mean (GM) and geometric standard deviation (GSD) of the number of exposure periods (exposure period = consecutive time (seconds) ≥1 % ICNIRP standards), the duration of exposure periods, their mean level of exposure, and maximum level of exposure per ISCO88 job code.

Mixed effects logistic regression models were used to assess potential determinants of exposure. The main outcome was defined as having any recorded value of at least 1 % of the ICNIRP 1998 occupational standards for a minimum of one second over the work shift. Sensitivity analysis was performed using different exposure durations and threshold level cut points. The analysis was conducted separately for E and H fields. Covariates assessed included basic socio-demographic information: sex, country, age group, dominant hand, any previous knowledge of RF-EMF; measurement information: year of measurement, season, representativeness of the measured work shift, practicality, exposimeter dysfunction, body location, COVID-19 impact on work organization; and occupational information: duration of work in current occupation, number of self-reported occupational sources used during the work shift, number of background sources, and personal mobile phone use and storage location during the workday. Random effects were applied for occupation (ISCO88 one-digit level) and the measurement device unit number to account for the within-group dependence. A backward stepwise selection process was followed to select the variables to be included in the final model, based on a threshold of $p \leq 0.1$. Potential collinearity between covariates was studied with Cramer's V matrices. Additional sensitivity analyses were also conducted by sex, removing participants reporting: a malfunctioning exposimeter, making phone calls with their personal mobile phone, reporting a bad practicality of the exposimeter, measurements with the exposimeter on the belt, and analyzing physiotherapists separately.

All measurement data were collected and extracted with the Radman 2-TS *Personal Monitor Transfer Software Version 1.0.0* (Narda) software. Statistical analysis of the measurements and data collected were performed with R software version 4.2.1, Copyright (C) 2022 The R Foundation for Statistical Computing.

2.5. Ethics

The study methodology and informed consent were approved by the Comité étic d'investigació CEIC-Parc de Salut Mar de Barcelona, and of the CEEI/IRB (Comité d'évaluation éthique de l'INSERM, International Review Board), IRB00003888, avis n°20-736 France.

3. Results

Overall, data on a total of 333 workers was collected during their full work shift in Spain (n = 285) and France (n = 48), totaling 1,991h of measurements. Selected characteristics of the participants are presented in Table 1. The majority of participants were male (60.7 %) and the mean age of the participants was 43.1 years (SD = 11.3). The mean work experience in the current occupation was 12.3 years (SD = 10.7). The

Table 1
General characteristics of measured participants (n = 333) classified by ISCO88 one-digit groups in Spain and France from 2021 to 2022.

		ISCO88 one-digit group									
		1 (n = 1) %	2 (n = 44) %	3 (n = 102) %	4 (n = 33) %	5 (n = 34) %	6 (n = 5) %	7 (n = 19) %	8 (n = 87) %	9 (n = 8) %	Total (n = 333) %
Sex	Female	–	63.6	52.9	42.4	76.5	–	–	8.1	25.0	39.3
	Male	100.0	36.4	47.1	57.6	23.5	100.0	100.0	92.0	75.0	60.7
Country											
	Spain	–	100.0	95.1	81.8	100.0	100.0	100.0	65.5	25.0	85.6
	France	100.0	–	4.9	18.2	–	–	–	34.5	75.0	14.4
Age group (years)											
	<30	–	22.7	14.7	–	14.7	–	5.3	8.1	12.5	11.7
	30–40	–	11.4	17.7	24.2	17.7	–	31.6	13.8	37.5	17.4
	40–50	–	9.1	31.4	54.6	26.5	–	31.6	19.5	12.5	26.1
	>50	–	34.1	13.7	12.1	32.4	20.0	21.1	17.2	–	19.2
Work experience (years)											
	<1	–	13.6	11.8	–	11.8	–	10.5	1.2	12.5	7.8
	1–5	–	13.6	19.6	33.3	32.4	–	21.1	19.5	25.0	21.3
	>5	–	38.6	46.1	54.6	41.2	20.0	63.2	33.3	50.0	42.6
Meter practicality											
	Bad	–	2.3	7.8	12.1	11.8	–	–	5.8	50.0	7.8
	Good	100.0	97.7	92.2	87.9	88.2	100.0	100.0	94.3	50.0	92.2
Meter dysfunction											
	No	–	100.0	98.0	93.9	97.1	80.0	100.0	98.9	75.0	97.0
	Yes	100.0	–	2.0	6.1	2.9	20.0	–	1.2	25.0	3.0
Body location											
	Belt	–	20.5	24.5	–	20.6	40.0	5.3	16.1	25.0	18.0
	Chest	100.0	79.6	75.5	100.0	79.4	60.0	94.7	83.9	75.0	82.0
Representativity of shift											
	Non-Typical	–	15.9	6.9	9.1	17.7	–	–	5.8	–	8.4
	Typical	100.0	84.1	93.1	90.9	82.4	100.0	100.0	94.3	100.0	91.6
COVID-19 impact on work organization											
	Affected	–	20.5	21.6	36.4	29.4	–	31.6	10.3	–	20.4
	Non-affected	100.0	79.6	78.4	63.6	70.6	100.0	68.4	89.7	100.0	79.6

Note: In some cases, there is missing data for some variables, where the variable total does not equal the total number of workers measured in each one-digit job code.

most frequent one-digit ISCO88 occupations included 3-*Technicians and associate professionals* (n = 102, 30.6 %), *8- Plant and machine operators and assemblers* (n = 87, 26.1 %), *2- Professionals* (n = 44, 13.2 %), *5- Service workers and shop and market sales workers* (n = 34, 10.2 %), and *4- Clerks* (n = 33, 9.9 %). Data on a total of 46 four-digit ISCO88 job codes were collected, with *Physiotherapists and associate professionals* (ISCO 3226, n = 66, 19.8 %), *Institution-based personal care workers* (ISCO 5132, n = 30, 9.0 %), *Papermaking-plant operators* (ISCO 8143, n = 19, 5.7 %), and *Lifting-truck operators* (ISCO 8334, n = 17, 5.1 %) being the most frequently measured occupations. Most workers reported good practicality of carrying the meter (92.2 %), that there was no apparent dysfunction of the meter during the measurement day (97.0 %), and that

Table 2
Self-reported occupational RF-EMF sources used by ISCO88 one-digit group and worker-diary occupational sector.

	ISCO88 one-digit group									
	1 (n = 1) %	2 (n = 44) %	3 (n = 102) %	4 (n = 33) %	5 (n = 34) %	6 (n = 5) %	7 (n = 19) %	8 (n = 87) %	9 (n = 8) %	Total (n = 333) %
1. Diagnosis and treatment										
Ultrasound therapy	–	2.9	44.1	–	5.9	–	–	–	–	14.4
Microwave therapy	–	2.9	28.4	–	14.7	–	–	–	–	10.5
Pulse short wave therapy	–	–	3.9	–	2.9	–	–	–	–	1.5
Continuous short wave therapy	–	–	3.9	–	5.9	–	–	–	–	1.8
Hyperthermia equipment	–	–	12.7	–	5.9	–	–	–	–	4.5
Surgical diathermies	–	–	2.0	–	–	–	–	–	–	0.6
TECAR	–	–	2.0	–	–	–	–	–	–	0.6
2. Heating food and medical dental				–						
Microwave heating	–	2.9	–	–	2.9	–	–	–	–	0.6
3. Industrial heating				–						
Induction heater/welder	–	–	–	–	–	–	5.3	–	–	0.3
Dielectric sealer/welder	–	–	–	–	–	–	5.3	2.3	–	0.9
Radiofrequency sealer/welder	–	–	1.0	–	–	–	5.3	2.3	–	1.2
4. Radar				–						
Distance measuring equipment	–	–	–	–	–	20.0	–	–	–	0.3
Radio beacons	–	–	–	–	–	20.0	–	–	–	0.3
8. Warehouse										
Wearable barcode scanner	–	–	–	21.2	–	–	–	12.6	50.0	6.6
9. Other										
Personnal communication services	–	2.9	–	12.1	2.9	–	5.3	4.6	25.0	3.9
Antitheft gates and object identification	–	–	1.0	–	–	–	–	–	25.0	0.9

*Occupational sectors 5-Semiconductors, 6-Telecommunication antennas, 7-Digital platform workers not shown due to no measurements performed in these groups.

the measurement day was representative of a typical working day (91.6 %). Some participants carried the exposimeter on their belt instead of their chest (n = 60, 18.0 %) such as hospital workers needing to perform close contact manipulations with patients.

A summary of the self-reported occupational sources of RF-EMF emitting devices used per ISCO88 one-digit code is presented in Table 2. *Technicians and associate professionals (group 3)* had the highest proportion of workers who reported the use of any specific RF-EMF occupational source (n = 51, 50 %). "Ultrasound diathermy equipment" was the most reported device used, with 48 workers, largely *Physiotherapists* (ISCO88 3226) reporting its use. Among other groups, the most frequently encountered RF-EMF occupational source was a "barcode scanner", found in ISCO88 groups *4 (Clerks), 8 (Plant and machine operators and assemblers), and 9 (Elementary occupations).* Almost 90 % of the respondents of the general sources section of the Worker Diary (n = 286) reported being exposed to Wi-Fi, 35.3 % used a microwave oven at least once during the day, and 33.2 % used any type of Bluetooth device. Regarding personal mobile phone use, 47.0 % sent text messages and 42.0 % made phone calls. The personal mobile phone was worn on the body (59.4 %), mainly in the trouser pocket. Otherwise, it was kept on the work table (20.8 %) or away from the work site (19.8 %), particularly among *Plant and machine operators and assemblers.* There were some differences regarding use of the personal mobile-phone by sex: with a greater proportion of female participants reporting using more than one mobile-phone feature during the work shift ($p < 0.005$). Females also more frequently reported having kept the personal-mobile phone on the work table than male participants ($p < 0.005$).

Exposure metrics are summarized in Table 3a (E-fields) and Table 3b (H-fields) among ISCO88 two-digit occupations. Additional exposure metrics at the four-digit level can be found in the Supplementary Material (Tables S.1.a, S.1.b and S.2). The mean (SD) measurement duration was 6 (1 h44) h overall. At the ISCO88 two-digit level, the mean (SD) measurement duration ranged from 3 h13 (0) for group *91-Sales and services elementary occupations* to 11 h09 (1 h43) for group *61-Market-oriented skilled agricultural and fishery workers* (Table S.3).

Overall, 50.2 % and 77.2 % of all measured workers were exposed (any one second measurement ≥1 % of the ICNIRP standard) to E and H fields respectively. Among exposed ISCO88 two-digit level codes, for E fields, the proportion of exposed workers, ranged from 27.8 % (group 72 - *Metal, machinery and related trades workers*) to 100 % (group 42 – *Customer services clerks;* group 91 – *Sales and services elementary occupations*). The proportion of measurements below the detection limit of the measurement device was >99 % of one second measurements across all exposed two-digit ISCO codes. The GM (GSD) number of exposure periods ranged from 1 ± 0.0 (group 34 – *Other associate professionals*) to 486.4 ± 1.9 (group 81 – *Stationary-plant and related operators*). The GM (GSD) duration of exposure periods was 1.7 (2.0) seconds overall. The longest duration of a single exposure period was 625s (group 32 – *Life science and health associate professionals*). The GM (GSD) level of exposure periods was 1.9 % (2.0) overall. The greatest maximal recorded exposure period value was 211.3 % (groups 42 – *Customer services clerks* & 51 – *Personal and protective service workers*). Results for H-fields appear

Table 3a
Measured occupations and exposure metrics calculated for each ISCO88 two-digit occupation having at least one exposed worker ≥1 % ICNIRP 1998 occupational standard for ≥1 s over the work shift for electric fields (E).

ISCO88 Code - Label	n workers	Exposure metrics[2]						
		Any exposure[1]	One second measurements above threshold (%)		Number of exposure periods	Duration of exposure periods (s)	Level of exposure periods (% ICNIRP)	Maximum level of exposure periods (% ICNIRP)
		%	≥1 %	≥100 %	GM (GSD)*	GM (GSD)*	GM (GSD)*	GM (GSD)*
21 - Physical, mathematical and engineering science professionals	16	37.5	<0.1	0.0	15.8 (2.0)	1.4 (1.5)	1.4 (1.6)	1.5 (1.7)
22 - Life science and health professionals	26	46.2	<0.1	0.0	23.7 (3.4)	1.5 (1.5)	1.7 (1.7)	1.9 (1.9)
31 - Physical and engineering science associate professionals	21	38.1	0.2	<0.1	49.0 (2.4)	3.4 (1.7)	7.4 (5.6)	9.2 (6.2)
32 - Life science and health associate professionals	78	71.8	1.0	<0.1	404.3 (3.9)	1.7 (2.0)	1.7 (1.6)	1.9 (1.9)
34 - Other associate professionals	3	33.3	<0.1	0.0	1.0 (NA)	1.0 (NA)	1.3 (NA)	1.3 (NA)
41 - Office clerks	30	36.7	0.1	0.0	107.8 (2.7)	1.3 (1.5)	1.6 (1.6)	1.7 (1.7)
42 - Customer services clerks	3	100.0	0.2	<0.1	12.7 (2.4)	2.1 (2.0)	2.9 (3.3)	3.4 (3.6)
51 - Personal and protective service workers	34	70.6	0.6	<0.1	304.3 (3.7)	1.8 (2.0)	1.9 (1.8)	2.2 (2.1)
61 - Market-oriented skilled agricultural and fishery workers	5	60.0	0.2	0.0	112.5 (2.1)	1.6 (1.7)	1.7 (1.5)	1.8 (1.6)
72 - Metal, machinery and related trades workers	18	27.8	0.1	0.0	56.9 (2.9)	1.6 (2.0)	2.0 (1.8)	2.3 (2.1)
81 - Stationary-plant and related operators	19	31.6	0.3	0.0	486.4 (1.9)	1.2 (1.4)	1.5 (1.5)	1.5 (1.5)
82 - Machine operators and assemblers	35	42.9	0.2	<0.1	85.8 (2.5)	1.8 (1.9)	2.3 (2.5)	2.6 (2.8)
83 - Drivers and mobile-plant operators	33	30.3	0.2	0.0	98.5 (2.9)	2.6 (1.9)	3.9 (2.3)	4.9 (2.5)
91 - Sales and services elementary occupations	1	100.0	1.0	0.0	94.0 (1.0)	1.2 (1.4)	1.3 (1.3)	1.3 (1.3)
93 - Labourers in mining, construction, manufacturing and transport	7	85.7	0.2	0.0	44.7 (3.1)	3.0 (1.8)	7.6 (3.2)	9.8 (3.6)
All participants	329	50.8	0.2	<0.1	259.1 (4.2)	1.7 (2.0)	1.9 (2.0)	2.1 (2.3)

*Geometric mean, geometric standard deviation.
[1] Occupations with no recorded exposures ≥1 %: ISCO 12-Corporate managers, *n* = 1; ISCO 23-Teaching professionals, *n* = 2; ISCO 71-Extraction and building trades workers, *n* = 1.
[2] The exposure metrics are calculated based on the exposure periods captured among each participant and summarized at the corresponding ISCO88 level (exposure period = consecutive time (in seconds) ≥1 % of ICNIRP standard).

Table 3b
Measured occupations and exposure metrics calculated for each ISCO88 two-digit occupation having at least one exposed worker ≥1 % ICNIRP 1998 occupational standard for ≥1 s over the work shift for magnetic fields (H).

ISCO88 Code - Label	n workers	Exposure metrics[2]						
		Any exposure[1]	One second measurements above threshold (%)		Number of exposure periods	Duration of exposure periods (s)	Level of exposure periods (% ICNIRP)	Maximum level of exposure periods (% ICNIRP)
		%	≥1 %	≥100 %	GM (GSD)*	GM (GSD)*	GM (GSD)*	GM (GSD)*
21 - Physical, mathematical and engineering science professionals	16	87.5	0.1	0.0	37.9 (2.7)	1.2 (1.4)	1.4 (1.4)	1.4 (1.4)
22 - Life science and health professionals	26	61.5	<0.1	0.0	13.5 (2.1)	1.3 (1.5)	1.6 (1.8)	1.7 (1.9)
23 - Teaching professionals	2	50.0	<0.1	0.0	3.0 (1.0)	1.3 (1.5)	1.4 (1.2)	1.4 (1.2)
31 - Physical and engineering science associate professionals	21	61.9	0.2	<0.1	53.7 (2.6)	2.6 (1.9)	3.6 (2.9)	4.3 (3.2)
32 - Life science and health associate professionals	78	88.5	0.7	<0.1	286.1 (4.7)	1.6 (2.0)	1.6 (1.6)	1.7 (1.8)
34 - Other associate professionals	3	66.7	<0.1	0.0	1.6 (1.5)	1.8 (1.7)	1.7 (1.4)	2.0 (1.6)
41 - Office clerks	30	56.7	0.1	0.0	139.9 (4.2)	1.3 (1.5)	1.5 (1.5)	1.6 (1.6)
42 - Customer services clerks	3	100.0	0.2	<0.1	19.6 (2.3)	1.3 (1.8)	1.7 (2.3)	1.8 (2.6)
51 - Personal and protective service workers	34	94.1	0.3	<0.1	64.8 (2.4)	1.4 (1.8)	1.5 (1.6)	1.7 (1.9)
61 - Market-oriented skilled agricultural and fishery workers	5	100.0	0.1	0.0	17.7 (2.0)	1.8 (1.8)	1.9 (1.5)	2.1 (1.6)
71 - Extraction and building trades workers	1	100.0	<0.1	0.0	1.0 (NA)	1.0 (NA)	1.1 (NA)	1.1 (NA)
72 - Metal, machinery and related trades workers	18	77.8	0.1	0.0	65.9 (3.3)	1.4 (1.6)	1.6 (1.6)	1.7 (1.7)
81 - Stationary-plant and related operators	19	68.4	0.1	0.0	42.3 (2.7)	1.3 (1.5)	1.5 (1.4)	1.6 (1.4)
82 - Machine operators and assemblers	35	82.9	0.4	<0.1	108.5 (2.9)	1.6 (1.8)	2.3 (2.6)	2.6 (2.9)
83 - Drivers and mobile-plant operators	33	63.6	0.5	<0.1	37.3 (2.4)	2.0 (2.4)	1.6 (1.9)	1.7 (2.1)
93 - Labourers in mining, construction, manufacturing and transport	7	100.0	0.3	0.0	48.8 (1.9)	1.8 (1.9)	2.5 (2.1)	2.9 (2.4)
All participants	331	77.6	0.2	<0.1	128.1 (4.6)	1.6 (1.9)	1.7 (1.9)	1.9 (2.1)

*Geometric mean, geometric standard deviation.
[1] Occupations with no recorded exposures ≥1 %: ISCO 12, Corporate managers, n = 1; ISCO 91, Sales and services elementary occupations, n = 1.
[2] The exposure metrics are calculated based on the exposure periods captured among each participant and summarized at the corresponding ISCO88 level (exposure period = consecutive time (in seconds) ≥1 % of ICNIRP standard).

in Table 3b.

Fig. 1 shows selected examples of instantaneous exposure levels observed among different occupations according to the type of occupational source used during the work shift. E field exposure values were truncated at 211.3 % likely due to the upper limit of detection of the meter. Fig. 2 provides a graphical representation of the GM level of each exposure period ≥1 % ICNIRP standards.

Following the backward stepwise selection process, the final model for both E and H fields included sex and use of any occupational source (Table 4). Female workers were more likely to be exposed ≥1 % of the ICNIRP standards compared to male workers, for E fields. Workers reporting use of any occupational source were more likely exposed than those who did not report use. In sensitivity analysis using different cut points of duration or level of exposure findings were generally similar though the positive association with female sex attenuated somewhat for E-fields.

Table S.4 shows occupations with at least one second measurement exceeding 100 % of the ICNIRP standard, at the ISCO four-digit level. The highest instantaneous exposure level recorded was up to 346 % and 353 %, for *Physiotherapists* (ISCO88 3226) and *Institution-based personal care workers* (ISCO88 5132) for H fields, with a GM (GSD) of exposure period duration of 4.4 (3.9) and 1.9 (1.6) seconds, respectively. The GM (GSD) of the maximum level of exposure was 139.5% (1.3) and 150.9% (1.4) for E fields and 215.4% (1.5) and 152.0% (1.3) for H fields respectively.

4. Discussion

Personal full-shift measurements of occupational exposure to RF-EMF were conducted in Spain and France among 333 workers from 46 ISCO88 four-digit occupations. Measurements for both E and H fields showed a large proportion of one second measurement values (>99 %) below 1 % of the ICNIRP 1998 occupational standards, though in some instances, measurements exceeding 100 % of the standards were observed in specific occupations such as *Physical and engineering science technicians* (ISCO88 3119), *Physiotherapists and other associate professionals* (ISCO88 3226), or *Institution-based personal care workers* (ISCO88 5132). Overall, a total of 50.2 % and 77.2 % of workers were ever exposed to E and H fields ≥1 % of the ICNIRP standards respectively.

Previous studies have measured occupational RF-EMF exposure to assess workers' health effects or compliance with occupational standards. Exposure to RF-EMF, emitted from environmental sources in occupational settings such as Wi-Fi, is low (Martínez-Búrdalo et al., 2009; Massardier-Pilonchery et al., 2019). Nevertheless, some specific occupations, such as those involving telecommunications, radars, military equipment, industrial or medical equipment, may expose workers to higher levels of RF-EMF that may exceed occupational standards often for a short duration over a shift. A review of literature on various occupational sources of RF-EMF showed that reference levels were occasionally exceeded in the immediate vicinity of plastic welding

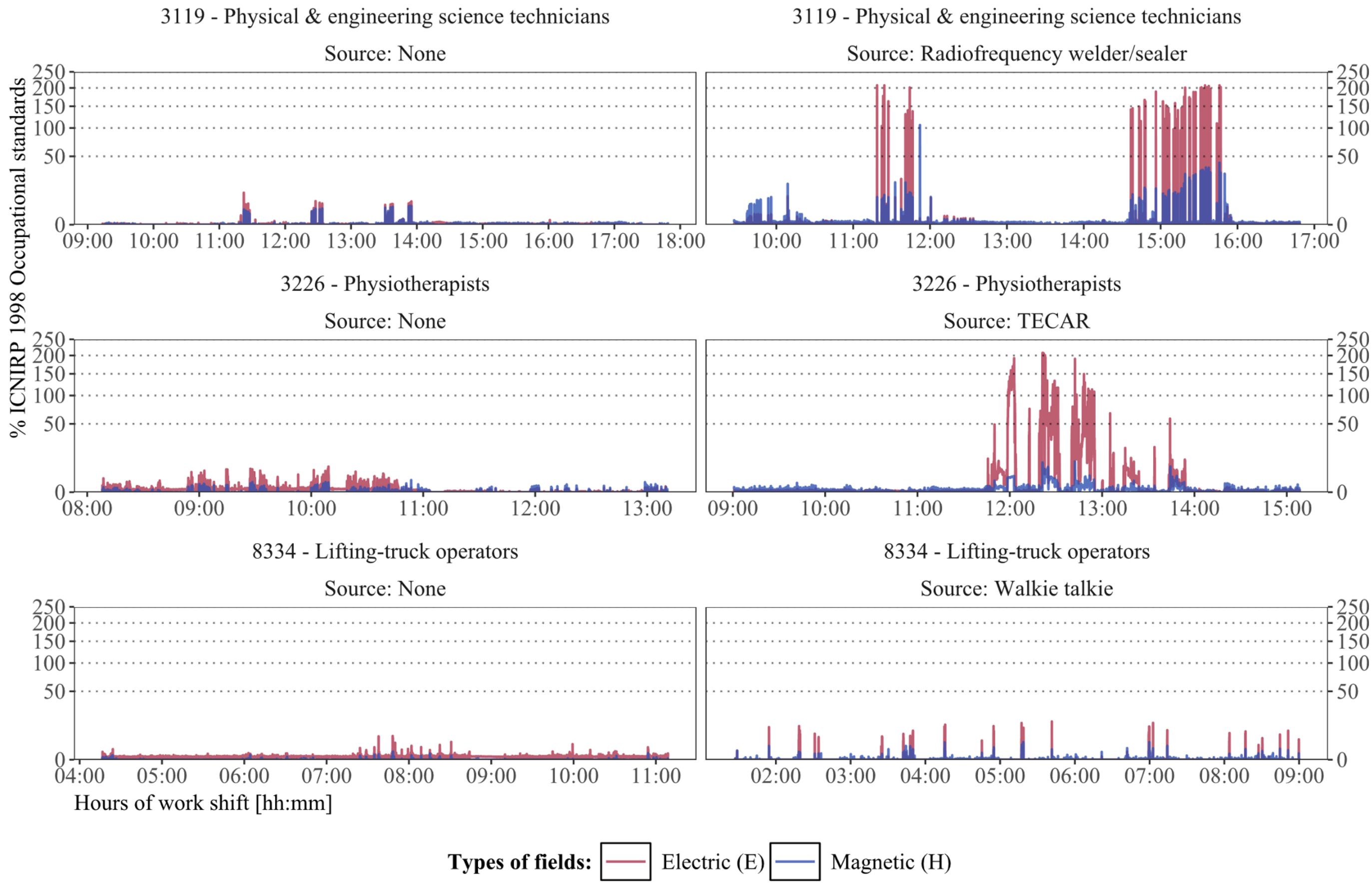

Fig. 1. Comparison of selected RF-EMF (instantaneous) exposure profiles of workers from the same measurement dates and sites, distinguishing those who did and did not self-report use of an occupational source of RF-EMF during their work-shift.

machines, security and RFID equipment, broadcasting and television antennas (Stam, 2022). It was also observed in relation to plasma devices, microwave drying and heating, and radars. Exposure of physiotherapists to RF-EMF has been studied (Andrikopoulos et al., 2017; Basiouka et al., 2020; Koutsojannis et al., 2018; Shah and Farrow, 2014; Shah and Farrow, 2013; Stam and Yamaguchi-Sekino, 2018) while there is limited information regarding institution-based personal care workers.

A major strength of this study was the conduct of personal measurements of exposure to RF-EMF across a full-shift for a broad range of occupations. Obtaining personal measurements of exposure to RF-EMF is important given potential biases inherent to other types of measurement methods (Röösli et al., 2010). We used the occupational meter Radman 2XT™, which allowed for a standardized measurement protocol applicable to a wide range of occupations. We used a one-second integration time, which was the smallest measurement sampling time of the device and also sought to balance exposure capture and device battery life (Röösli et al., 2010). We used the max hold value to summarize exposures per second, focusing on recording the highest exposures during each measurement. A high proportion of participants reported good practicality of performing typical work tasks wearing the meter.

A limitation of this study is the frequency shaped measurement design of the meter that prevented obtaining frequency-specific results. There are also potential limitations regarding body shielding (Bhatt et al., 2016), the frequency range covered, and the absence of frequency specific output. As an example, sources such as microwave therapy equipment are usually operated at a frequency of 2.45 GHz (Vila et al., 2016), which is outside of the measurement range of the Radman 2XT™ H antenna [27 MHz–1 GHz] (Narda safety test solutions, 2023b). This may have resulted in an underestimation of some exposures to H fields. Furthermore, while many measurement devices are primarily designed for assessing far-field exposure conditions, the measurement device used here, with its dual E and H antennas, allows for reliable measurement of both near-field and far-field exposures within its specific frequency limits (*Supplementary Material*, Table S.5).

In addition, the high detection threshold and low sensitivity (<1 %) of the measurement device limited our ability to detect low-intensity RF-EMF sources present in many occupations, such as Wi-Fi, mobile phones, and other telecommunication networks. Although our primary aim was to measure major occupational exposures, we focused on measurements at or above 1 % ICNIRP where they are considered reliable. Furthermore, the high proportion of values below 1 % ICNIRP among most workers (>99 %) rendered time-weighted average exposure calculations of limited informativeness. The high proportion of values below 1 % may also complicate comparisons with previous studies (Migault et al., 2019).

The output of the device is provided on the basis of the ICNIRP 1998 occupational standards, despite the implementation of a new standard during the course of the study (International Commission on Non-Ionizing Radiation Protection (ICNIRP), 2020). The meters were however compliant with the new standards for measurements above 27 MHz. However, given the few captured sources emitting below 27 MHz, the impact on our findings is likely small.

Other potential limitations include limited participation of workers from ISCO88 occupations considered more likely to be highly-exposed based on the current RF-JEM estimates. Despite attempts to recruit from these occupations, only a small proportion of participants belonging to presumed higher-exposed occupations participated. Additionally, an important proportion of the Spanish measurements were

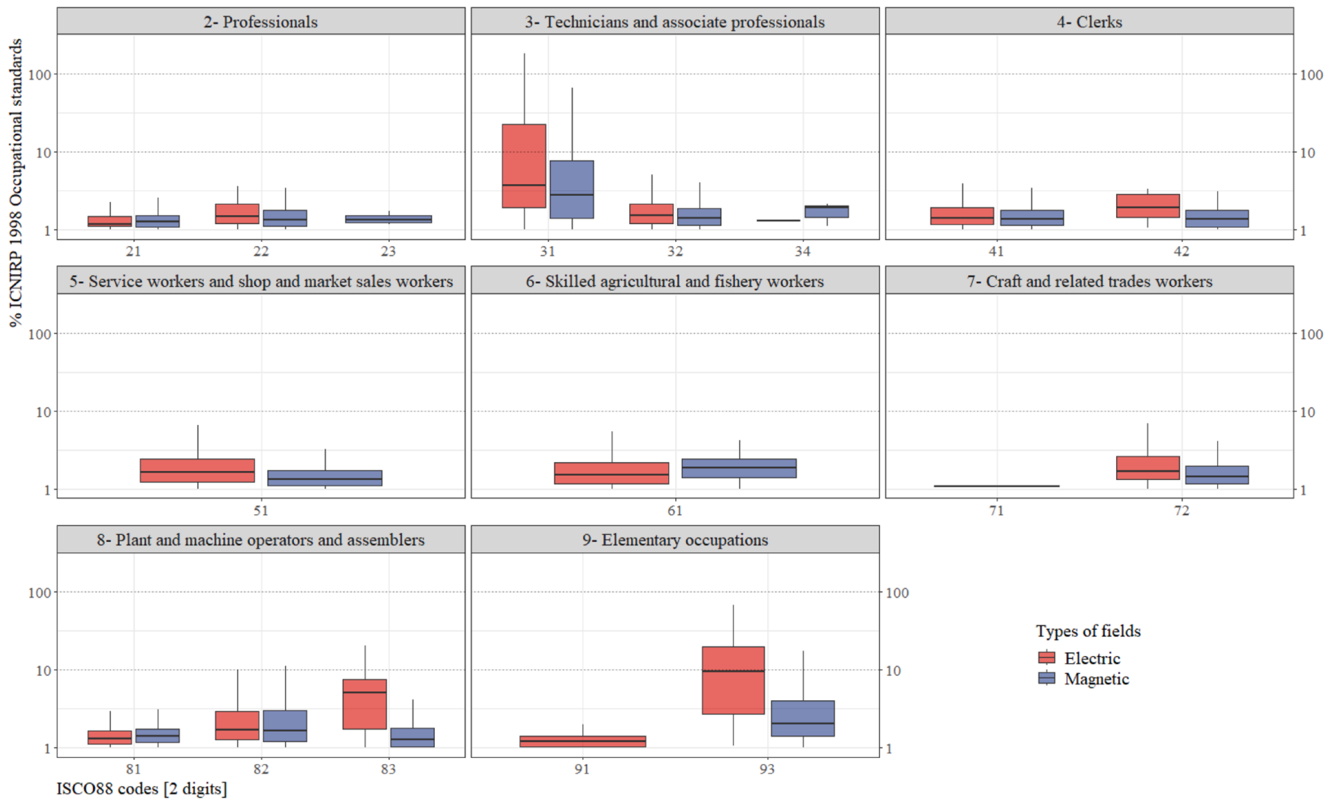

Fig. 2. Distribution of the GM exposure levels (25th, 50th, and 75th percentiles in % ICNIRP, outliers not shown) across exposure periods per ISCO88 2- digit occupational code for workers with measured exposure ≥1 % ICNIRP 1998 standard ≥1 s over the work shift, E and H fields.

Table 4
Mixed effects logistic regression models of determinants of exposure to E and H fields (n = 333).

Covariates	n	Electric fields (E)				Magnetic fields (H)			
		Non-exposed	Exposed	OR[2]	95 % CI[3]	Non-exposed	Exposed	OR[2]	95 % CI[3]
		n = 166[1]	n = 167[1]			n = 76[1]	n = 257[1]		
Main analysis (any exposure ≥ 1% ICNIRP 1998 standard ≥ 1 second over the work shift).									
Sex	333								
Male		118 (71.1 %)	84 (50.3 %)	—	—	52 (68.4 %)	150 (58.4 %)	—	—
Female		48 (28.9 %)	83 (49.7 %)	2.77	1.57. 4.90	24 (31.6 %)	107 (41.6 %)	1.79	0.97. 3.29
Self-reported occupational source used	333								
None		144 (86.7 %)	115 (68.7 %)	—	—	74 (97.3 %)	185 (72.0 %)	—	—
One or more		22 (13.3 %)	52 (31.3 %)	3.03	1.59. 5.77	2 (2.7 %)	72 (28.0 %)	15.6	3.69. 66.0
Sensitivity analysis (any exposure ≥1 % ICNIRP 1998 standard ≥24.8 s (E-fields) or ≥18.1 s (H-fields) over the work shift[4]).									
		Non-exposed	**Exposed**			**Non-exposed**	**Exposed**		
		n = 249[1]	**n = 84**[1]			**n = 210**[1]	**n = 123**[1]		
Sex	333								
Male		157 (63.1 %)	45 (53.6 %)	—	—	139 (66.2 %)	63 (51.2 %)	—	—
Female		92 (36.9 %)	39 (46.4 %)	1.74	0.93. 3.26	71 (33.8 %)	60 (48.8 %)	2.13	1.25. 3.65
Self-reported occupational source used	333								
None		213 (85.5 %)	46 (54.8 %)	—	—	180 (85.7 %)	79 (64.2 %)	—	—
One or more		36 (14.5 %)	38 (45.2 %)	4.92	2.60. 9.34	30 (14.3 %)	44 (35.8 %)	3.41	1.91. 6.07

*Random effects for the Radman 2XT™ unit and ISCO88 1-digit level job code.
[1] *n* (%).
[2] OR = Odds Ratio.
[3] 95 % Confidence Interval.
[4] Duration cut points for E and H fields were based on the geometric mean of cumulative duration ≥1 % ICNIRP standard calculated over all participants.

conducted during the COVID-19 pandemic, which may have impacted exposure measurements due to changes in work organization and reduced participation of companies, though the majority of workers reported that their work tasks were unaffected.

Knowledge of occupational RF-EMF sources and exposure among participants was typically low, which may have hindered company interest and participation, as well as impacted questionnaire responses regarding exposure to RF-EMF sources, potentially leading to under-reporting of sources used. Additionally, in our sample of institution-based personal care workers, which was mostly drawn from rehabilitation departments, workers often worked in proximity to RF-EMF equipment (e.g. diathermy equipment), to which they were exposed as a bystander but which were not captured in the worker diary as only sources used by the participant were queried (70.0 % of institution-based personal care workers were exposed while 26.7 % reported use of an RF-EMF emitting device, compared with 69.7 % of physiotherapists exposed and 75.6 % who reported use of an RF-EMF emitting source).

Regarding our main analysis of determinants of RF-EMF exposure, the increased E field exposure of females may be attributable to their greater proportion in the medical sector, where we encountered a higher prevalence of occupational RF-EMF sources.

Within-worker variability of exposure could not be studied as all participants and companies only accepted to participate for one work-shift per worker. Within-worker exposure variability is important to be considered, especially in highly exposed occupations (Bolte, 2016; Röösli et al., 2010). To address variability within a given occupational code, we attempted to oversample workers from the same occupation, whenever possible (21 % of ISCO88 four-digit codes $\geq$10 workers; 63 % $\geq$3 workers). There are differences observed within jobs due to occupational sources used and tasks performed. Additional measurements of more highly-exposed occupations, along with a thorough evaluation of the sources used is needed in future work. Expert assessment may be required to identify or verify the self-reported sources used for each occupation. Additional measurements are also needed in a broader range of countries. There is uncertainty regarding the most relevant metric of exposure, as current occupational standards are based on the thermal effects of RF-EMF exposure, and there is no clear rationale linking RF-EMF exposure and potential non-thermal effects (Röösli, 2014).

5. Conclusion

In this study, RF-EMF levels of 333 workers from 46 four-digit ISCO88 occupations were measured. We found that overall levels of exposure to RF E and H fields were low, but short high-intensity exposure periods occurred in a few specific occupations, some exceeding the level of the ICNIRP occupational standards. Our analysis showed that females and workers reporting use of any relevant occupational tool/apparatus were more likely to be exposed within a shift to RF E and/or H fields at or above 1 % of the ICNIRP standards. Further research to capture both within- and between-worker variability of exposure with assessment of the sources used in each job to obtain reliable estimates of exposure at the job level is warranted, as is oversampling of more highly-exposed occupations in different regions, industries or work environments.

Author contributions statement

Mr. Maxime Turuban: Mr. Turuban was involved in data collection and carried out the majority of the data analysis. He authored the initial draft of the manuscript and made important contributions to the revised version.

Professor Hans Kromhout: Professor HK contributed to the project's original idea and conceptualization, provided valuable inputs during manuscript drafting and data analysis, and played a significant role in the revision of the manuscript.

Dr. Javier Vila: Dr. JV contributed to the development of the original idea, offered insightful inputs during manuscript preparation and data analysis, and played a significant role in the revision of the manuscript.

Mr. Miquel Vallbona-Vistós: Mr. MVV conducted a portion of the data analysis and offered contributions in the manuscript revision process.

Professor Isabelle Baldi: Professor IB contributed to the formation of the original idea and provided assistance in the manuscript revision process.

Dr. Michelle C. Turner: Dr. MT contributed to the original concept, was involved in the project's conceptualization, organized meetings, managed schedules, and played a crucial role in revising the manuscript. Conceptualization, Formal analysis, Funding acquisition, Methodology, Project administration, Supervision, Writing – review & editing.

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All authors have approved this version for publication and accept accountability for all aspects of the work.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available upon a reasonable request.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2023.108156.

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