Environmental Research 154 (2017) 160–170

Contents lists available at ScienceDirect

Environmental Research

journal homepage: www.elsevier.com/locate/envres

Measurements of intermediate-frequency electric and magnetic fields in households

Sam Aerts[a,*], Carolina Calderon[b], Blaž Valič[c], Myron Maslanyj[b], Darren Addison[b], Terry Mee[b], Cristian Goiceanu[b], Leen Verloock[a], Matthias Van den Bossche[a], Peter Gajšek[c], Roel Vermeulen[d], Martin Röösli[e,f], Elisabeth Cardis[g], Luc Martens[a], Wout Joseph[a]

[a] Department of Information Technology, Ghent University/iMinds, iGent, Technologiepark-Zwijnaarde 15, B-9052 Ghent, Belgium
[b] Centre for Radiation, Chemical and Environmental Hazards, Public Health England, Chilton, Didcot, Oxon OX11 0RQ, United Kingdom
[c] Institute of Non-Ionizing Radiation (INIS), Pohorskega bataljona 215, Ljubljana 1000, Slovenia
[d] Institute for Risk Assessment Sciences, Department of Environmental Epidemiology, Utrecht University, Yalelaan 2, 3508 Utrecht, The Netherlands
[e] Swiss Tropical and Public Health Institute (Swiss TPH), Socinstrasse 57, P.O. Box, 4002 Basel, Switzerland
[f] University of Basel, Petersplatz 1, 4003 Basel, Switzerland
[g] Barcelona Institute for Global Health (ISGlobal) and Municipal Institute of Medical Research (IMIM-Hospital del Mar), Doctor Aiguader, 88, 08003 Barcelona, Spain

ARTICLE INFO

Keywords:
Electric and magnetic fields
Human exposure
Intermediate frequencies
Household appliances
Epidemiology

ABSTRACT

Historically, assessment of human exposure to electric and magnetic fields has focused on the extremely-low-frequency (ELF) and radiofrequency (RF) ranges. However, research on the typically emitted fields in the intermediate-frequency (IF) range (300 Hz to 1 MHz) as well as potential effects of IF fields on the human body remains limited, although the range of household appliances with electrical components working in the IF range has grown significantly (e.g., induction cookers and compact fluorescent lighting). In this study, an extensive measurement survey was performed on the levels of electric and magnetic fields in the IF range typically present in residences as well as emitted by a wide range of household appliances under real-life circumstances. Using spot measurements, residential IF field levels were found to be generally low, while the use of certain appliances at close distance (20 cm) may result in a relatively high exposure. Overall, appliance emissions contained either harmonic signals, with fundamental frequencies between 6 kHz and 300 kHz, which were sometimes accompanied by regions in the IF spectrum of rather noisy, elevated field strengths, or much more capricious spectra, dominated by 50 Hz harmonics emanating far in the IF domain. The maximum peak field strengths recorded at 20 cm were 41.5 V/m and 2.7 A/m, both from induction cookers. Finally, none of the appliance emissions in the IF range exceeded the exposure summation rules recommended by the International Commission on Non-Ionizing Radiation Protection guidelines and the International Electrotechnical Commission (IEC 62233) standard at 20 cm and beyond (maximum exposure quotients EQ_E 1.0 and $_EQ_H$ 0.13).

1. Introduction

Electric appliances have become almost indispensable in our households. Connection to a power supply and use of electricity, however, leads to the emission of electric (EF) and magnetic fields (MF). To safeguard the general public from possible adverse health effects (such as electrostimulation) caused by EF and MF at frequencies typical for household appliances (i.e., lower than 1 MHz), their fields are subject to limits based on recommendations by international bodies such as the International Commission on Non-Ionizing Radiation Protection (ICNIRP, 2010) and the Institute of Electrical and Electronics Engineers (IEEE) International Committee on Electromagnetic Safety (ICES) (IEEE, 2006). Technical standardisation bodies such as the International Electrotechnical Commission (IEC) and the European Committee for Electrotechnical Standardization (CENELEC) use these guidelines as the basis for specific emission standards which enable manufacturers to demonstrate that their products are safe.

Historically, measurements of electromagnetic exposure from household appliances (e.g., Addari, 1994; Ainsbury et al., 2005; EPA, 1992; Karipidis and Martin, 2005; Leitgeb et al., 2008a, 2008b) and in residential environments (e.g., Addari, 1994; Preece et al., 1997;

* Corresponding author.
E-mail address: sam.aerts@intec.ugent.be (S. Aerts).

http://dx.doi.org/10.1016/j.envres.2017.01.001
Received 6 October 2016; Received in revised form 22 December 2016; Accepted 2 January 2017
Available online 10 January 2017

UKCCS, 2000; Tomitsch and Dechant, 2015) have focused on the *extremely-low-frequency* (ELF) range, between 1 Hz and 300 Hz, as the mains frequency (i.e., 50 Hz or 60 Hz) posed the dominant contribution. However, while the range of household appliances with electrical components working in the *intermediate-frequency* (IF) range (300 Hz to 1 MHz) has grown significantly in recent years (e.g., induction cookers and compact fluorescent lighting), there is still only limited information available on either the typical strength of the IF fields emitted by household appliances and on the typical human exposure to IF fields at home (Gajšek et al., 2016; Litvak et al., 2002; WHO, 2005).

Previous research on IF field emitting sources has tended to focus either on occupational sources (Aerts et al., 2014; Floderus et al., 2002; Joseph et al., 2012a, 2012b; Liljestrand, 2003; Nelson and Ji, 1999; Van den Bossche et al., 2015; VMBG, 2003; Wilén, 2010) or on non-residential appliances such as electronic article surveillance (EAS) systems (Harris et al., 2000; Joseph et al., 2012c; Kang and Gandhi, 2003; Martínez-Búrdalo et al., 2010; Roivainen et al., 2014; Trulsson et al., 2007), smartboards, and touch screens (Van den Bossche et al., 2015). Research on residential IF sources, on the other hand, is limited. There has been some research on induction cookers (Christ et al., 2012; Kos et al., 2011; Mantiply, 1997; Stuchley and Lecuyer, 1987), energy saving lamps (Bakos et al., 2010; Nadakuduti et al., 2012; Van den Bossche et al., 2015), portable hearing units (Van den Bossche et al., 2015), plasma balls (Alanko et al., 2011), and magnetic-field measurements were performed in a brief survey (Kurokawa et al., 2004). However, no surveys have yet been performed that address specifically typical IF field levels in the home.

In this paper, the results of a residential IF field emission survey spanning 42 residences in three European countries (Belgium, Slovenia, and the United Kingdom (UK)) are presented. Typical field levels in the properties were assessed by measurements in the middle of the most-frequented rooms (living room, kitchen, and bedroom), as reported by residents. The IF fields emitted from a wide range of household appliances were also investigated through measurements as a function of distance performed on 279 appliances, operating under real-life circumstances. This study, which focuses on exposure characterisation in everyday circumstances for epidemiological purposes, substantially extends current knowledge of typical IF fields in people's homes.

2. Materials and methods

2.1. Measurement equipment

To characterize the IF field levels in residences from household appliances, three measuring devices were used: a compact handheld meter (NFA-1000, Gigahertz Solutions, Langenzenn, Germany) and two computer-operated narrowband probes (EHP-50 and EHP-200, Narda Safety Test Solutions, Milan, Italy).

The NFA-1000 is able to (separately) measure the environmental magnetic- (H, in A/m) and the electric-field strength (E, in V/m) in the frequency range between 5 Hz and 1 MHz, with dynamic measurement ranges of 0.8 mA/m to 1.6 A/m and 0.1 V/m to 2 kV/m, respectively. Measurements can be performed wideband (i.e., over the whole frequency range) as well as narrowband (i.e., in separate frequency bands: 16.7 Hz, 50 Hz, even harmonics up to 250 Hz, uneven harmonics up to 250 Hz, the remainder of frequencies below 2 kHz, and the frequency range between 2 kHz and 1 MHz).

The EHP-50 (with dynamic measurement ranges of 0.005 V/m to 100 kV/m (E) and 0.24 mA/m to 8 kA/m (H)) and EHP-200 (0.02–1000 V/m (E) and 0.6 mA/m–300 A/m (H)) probes were used to acquire EF and MF spectral information in their respective frequency ranges of 5 Hz to 100 kHz and 9 kHz to 30 MHz. When taking into account linearity, isotropy and frequency response, the expanded uncertainty (k=2) for the EHP probes was 8% and 15%, respectively. Assuming a conservative uncertainty of 10 °C in temperature and 10% in humidity, the expanded uncertainty respectively becomes 10% and 16%. Furthermore, to mitigate the uncertainty due to the spatial displacement of the X-, Y-, and Z-sensors in the EHP probes (which can amount to 28% according to Nadakuduti et al. (2012)), the top of the probe was always directed towards the appliance under assessment (Christ et al., 2012).

The EHP probes have been designed to have no or minimum perturbation of the fields that are being measured, and the tripod used to hold the probes was made of low permittivity materials. Also, the EHP probes were connected to a laptop via an optical cable, allowing measurements to be made several metres away. Thus, perturbation of the electric field was kept to a minimum.

To obtain a complete sweep of the frequency range relevant to the study, measurements were performed using the 2 kHz and 100 kHz measurement bands of the EHP-50 (i.e., 5 Hz to 2 kHz and 1 kHz to 100 kHz ranges, respectively) and also in the frequency range 9 kHz to 400 kHz (further called 400 kHz band) with the EHP-200, at a resolution bandwidth of 3 kHz. For each measurement, the maximum-hold setting was used, i.e., the maximum values were retained during a time interval until the reading stabilized (roughly 30 s). The 2 kHz band was necessary to capture the 300 Hz to 1 kHz range, but the results were mainly used for illustration.

2.2. Measurement procedure

2.2.1. Selection of residences

In total, 42 residences were investigated; 11 in Belgium, 16 in Slovenia, and 15 in the UK. This resulted in the measurement of the level and composition of environmental IF fields in 121 rooms and of 279 household appliances. The residences were from a convenience sample, and included detached, semi-detached and attached houses as well as apartments. The residents were interviewed to obtain information related to the time spent in different rooms and the use of electrical appliances found in the residence.

2.2.2. Spectral survey of the residence

To obtain a general idea of the strength of environmental IF fields in the property, two spot measurements were performed in a number of rooms – usually three, and ideally the ones in which the residents reported spending most of their time – one when the room was in 'hibernation mode' (i.e., the normal state of the room when no one is at home) and one during 'maximum living mode' (i.e., all EMF sources – lights, displays, kitchen appliances, etc. – normally in the room switched on, as far as this was feasible). During both usage modes, the ELF and IF fields in the room were characterised using the EHP probes, secured to a tripod positioned in the middle of the room, at 1.5 m above the floor.

2.2.3. Characterisation of IF emitting appliances

By measuring E and H in the 2 kHz to 1 MHz band solely, the NFA-1000 m enabled the quick identification of IF field emitting household appliances. When an appliance was identified as an IF source, the emitted IF fields were subsequently characterised with the EHP probes while the appliance was operated at settings typical for the residents. The probe was positioned in front of the face of the appliance closest to the user, or, for appliances with no preferential orientation, in front of the face where the highest exposure was detected. All measurements were taken at mid-height of the appliance, except for lighting sources, for which the measurements were performed in the direction of use (i.e., down when the lighting source was hanging from the ceiling and sideways when standing).

In the following, the measuring distance was defined as 'the distance between the surface of the appliance and the closest point of the sensor surface' (International Electrotechnical Commission (IEC), 2005). Although some previous studies opted to focus on the exposure

close to the source (15 cm and closer) (Bakos et al., 2010; Christ et al., 2012; Ishihara et al., 2015; Kos et al., 2011; Nadakuduti et al., 2012; Van den Bossche et al., 2015) or on compliance measurements at 30 cm (IEC, 2005), in this study, measurements were executed at 20 and 50 cm to assess the exposure as a function of distance in a larger region of space.

2.3. Exposure assessment

Exposure assessment of an EF and/or MF emitting source is typically done by comparing the levels of the emitted fields to reference levels $F_R(f)$ (with F=E or H, and f the frequency of the field) recommended by ICNIRP (2010). Reference levels for IF fields are conservatively derived for more practical hazard assessment from basic restrictions issued in terms of the internal EF. While compliance with the reference levels ensures compliance with the basic restrictions, exceeding them does not necessarily mean non-compliance, and more detailed assessment is needed (e.g., Sunohara et al., 2015).

Furthermore, to assess the total exposure of an IF source, the contributions of the different spectral components of the emitted fields (the results at f between 300 Hz and 2 kHz were taken from the 2 kHz measurement, between 2 kHz and 9 kHz from the 100 kHz measurement, and between 9 kHz and 400 kHz from the 400 kHz measurement) have to be added. To do this, the Exposure Quotient (EQ) was calculated following two methods: ICNIRP (2010), where the EQ is given by the sum of the weighted components (Eq. (1) in Table 1) and IEC 62233:2005 (IEC, 2005), where the EQ is given by the root-sum-square (RSS) of the weighted spectral components (Eq. (2) in Table 1). Only the peak field strengths $F_{peak,\,i}$ (measured at frequency f_i) which are higher than 5% of the corresponding reference level $F_{R,\,i}$ (e.g., for f_i between 3 kHz and 150 kHz, $E_{R,\,i}$ is 83 V/m and $H_{R,\,i}$ is 21 A/m) (ICNIRP, 2010) were considered in the EQ calculation (IEC, 2005), though this threshold was not defined in the ICNIRP guidelines.

3. Results and discussion

In this Section, first, the room measurements are discussed, then the IF characterisation of the household appliances, and finally a number of exposure-relevant appliances are considered in more detail.

3.1. Spectral survey of residences

A total of 121 rooms were surveyed (Table 2), with the three most common types (i.e., most visited by residents) bedrooms, kitchens, and living rooms. The wideband measurement results (E_{wide} and H_{wide}) were pooled per assessed frequency band and room usage mode (Fig. 1), and for the 100 kHz band are also discussed per most-common room type (Fig. 2).

Considering the absence of IF fields in hibernation mode, the probes' noise contributions in the 100 kHz band (EHP-50) and 400 kHz band (EHP-200) were at most 0.7 V/m (100 kHz: geometric mean (GM) 0.4 V/m; 400 kHz: GM 0.6 V/m) (Fig. 1a) and 0.10 A/m (100 kHz: GM 0.05 A/m; 400 kHz: GM 0.09 A/m) (Fig. 1b), respectively. With the rooms in maximum-living mode, the total electric-field strength in the 100 kHz band (which comprises most fundamental frequencies (f_f) of IF-field emissions) was on average (GM, considering all rooms) 1.2 V/m (geometric standard deviation (GSD): 2.6), an increase of 170% over the average noise floor (Fig. 1a), and maximum 9.5 V/m. However, in neither usage mode were any IF-MF emissions detected. The ELF emissions (as measured in the 2 kHz band), on the other hand, increased on average by 65% (E_{wide}) and 40% (H_{wide}) in the maximum-living mode as opposed to hibernation mode (Fig. 1b).

The same trend is observed per (most-common) room type (Fig. 2). Moreover, a higher spread in E wide was measured in kitchens (GSD: 3.1) and living rooms (GSD: 2.6) compared to bedrooms (GSD: 1.9)

Table 1
IEC (2005) and ICNIRP (2010) guidelines on comparing electric- (EF) and magnetic-field (MF) measurements at different frequencies lower than 10 MHz with the reference levels. $F_{peak,\,i}$ is a spectral peak in the EF (F=E) or MF (F=H) at frequency f_i, for which $F_{R,\,i}$ is the corresponding reference level.

Guidelines	Formula	Explanation	Eq. no
ICNIRP (2010)	$EQ_{F,\,ICN} = \sum_{i=1}^{N} \frac{F_{peak,\,i}}{F_{R,\,i}}$	Frequency-weighted sum restricted to N peaks ($F_{peak,\,i}$ not defined)	(1)
IEC 62233:2005	$EQ_{F,\,IEC} = \sqrt{\sum_{i=1}^{N} \left(\frac{F_{peak,\,i}}{F_{R,\,i}}\right)^2}$	Square root of quadratic sum restricted to N spectral peaks, with $F_{peak,\,i} > 0.05 \times F_{R,\,i}$	(2)

Table 2
Number of samples (n_r) of each room type.

Room type	n_r
Bedroom	40
Kitchen	35
Living room	35
Corridor	3
Study	4
Utility room	2
Dining room	2
Total	121

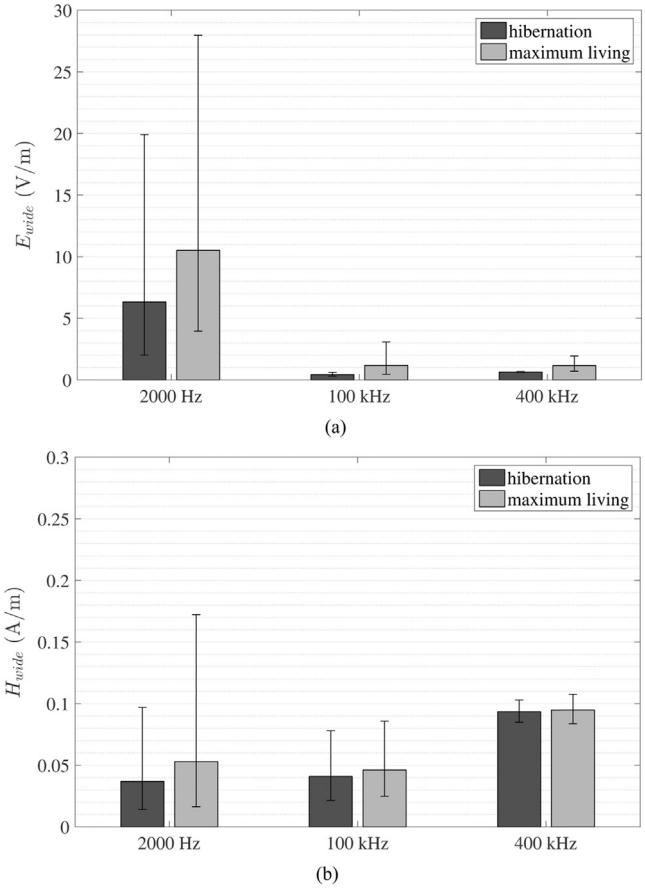

Fig. 1. Geometric means (and geometric standard deviations) per frequency band (EHP-50: 2 kHz and 100 kHz *bands*; EHP-200: 400 kHz *band*) and per room usage mode (hibernation/maximum living) of the (a) wideband *electric-field* strength measurements (E_{wide}, V/m) and (b) wideband *magnetic-field* strength measurements (H_{wide}, A/m), collected over all rooms (Table 2).

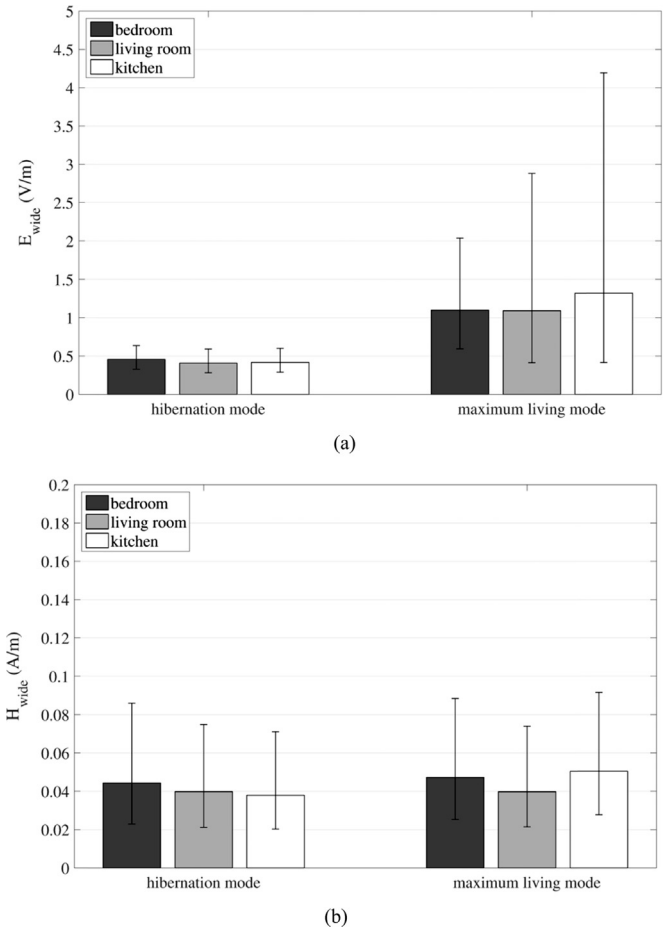

Fig. 2. Geometric means (and geometric standard deviations) per room type (showing only the three most-frequented rooms: bedroom/living room/kitchen) and per room usage mode (hibernation/maximum living) of the (a) wideband *electric-field* strength (E_{wide}, V/m) and (b) wideband *magnetic-field* strength (H_{wide}, A/m) measurements, collected over all rooms of the respective type in the 100 kHz *band* (measured with EHP-50).

when in maximum-living mode (Fig. 2a), reflecting the fact that there is a larger variety of electric appliances used in the former two. No substantial difference was observed in *H* across the rooms (Fig. 2b).

It should finally be noted that all measured values—remember that the measurements were performed at a distance of 1 m or more from any appliance—were very low compared to IF exposure guideline reference levels.

3.2. Source measurements

3.2.1. Overview

3.2.1.1. Appliances. Per residence, between 2 and 19 electric appliances (on average 7) were identified as IF emitters. The total of 279 appliances were further classified into 65 categories (Table 3), of which *power tools* and *compact fluorescent lamps* were the largest. Four more categories consisted of more than ten appliances, and 32 categories contained only one. Three categories (i.e., fridges, laundry machines, and microwave ovens) were split in two because part of the appliances used inverter technology (IT), causing distinct IF emissions (see Section 3.3.1). Furthermore, for some categories, multiple measurements were performed for each individual appliance. For example, measurements were taken at different times during operating cycles of dishwashers and laundry machines, and measurements of electric toothbrush chargers were taken with and without the toothbrush connected. Hence, in these cases, the number of measurement samples (n_s in Table 3.2) is higher than the number of appliances (#).

3.2.1.2. Measurements. All appliances assessed (Table 3) showed non-zero IF field emissions when measured with the NFA-1000 m. However, due to some of the low levels encountered and the sharp decrease in fields with distance, the fields for 24 out of the 65 categories of appliances investigated were not detectable at 20 cm and thus were not included in the summary of results (Table 4). Some of these appliances (e.g., compressor, portable radio, and vaporiser) did, however, emit strong EF and/or MF in the ELF range (data from EHP-50 2 kHz measurements, not shown here), which might explain the non-zero reading in the 2 kHz to 1 MHz band of the NFA-1000 m.

At 20 cm, wideband electric- (E_{wide}) and magnetic- (H_{wide}) field strengths were measured of up to 42.70 V/m (liquid-crystal display (LCD); 19.59 V/m at 50 cm) and 3.71 A/m (induction cooker; 0.82 A/m at 50 cm), respectively, with respective median values of 1.30 V/m (0.67 V/m at 50 cm) and 0.09 A/m (0.05 A/m at 50 cm). Furthermore, the IF-field spectra encountered in this study were found to be either well-defined and repeatable (e.g., CFLs or CRT displays, Fig. 3a), or complex and erratic (e.g., blenders, Fig. 3b).

Fig. 4 further offers a graphical overview of the range of the wideband EF and MF levels between 1 kHz and 100 kHz measured at a distance of 20 cm from the assessed sources. For clarity, only those categories with $n_s > 3$ that contained at least one appliance for which either field value at 20 cm was higher than 1% of the respective reference level above 3 kHz (i.e., 0.83 V/m or 0.21 A/m) are shown here. Overall, the category with the (consistently) highest measured IF fields – EF and MF – was *induction cooker* (light-green area in Fig. 4), after which *LCD*, *power tools* (albeit with a huge variation – see orange area in Fig. 4), *CFLs* (and other *fluorescent lighting*), and *microwave ovens* (*IT*) generated the highest fields.

3.2.1.3. Exposure quotient. For each source, the IF-EQs were calculated using two methods – IEC 62233:2005 and ICNIRP (2010) (Eqs. (1) and (2) in Section 2.3). In Fig. 5, these two methods were compared for both MF (blue diamonds) and EF (yellow circles) emissions.

Only in the case of a single dominant peak was EQ_{ICN} equal to EQ_{IEC}. For sources where several frequency components were above the 5% threshold(e.g., multiple components of a broad peak, or multiple harmonics), EQ_{ICN} was on average 56% higher, and maximally 112%. Had we not restricted the contribution of spectral components to those above 5% of the reference levels (as it was not defined as such in the ICNIRP guideline), the difference would have been larger.

Although all IF-field emissions measured at 20 cm satisfied both guidelines (EQ≤1), fourteen categories were considered exposure-relevant, i.e., they included at least one source with EQ > 0.05 (see Section 3.2.2.). Finally, although some EQs were close (or equal) to 1, the ICNIRP reference levels are designed to be quite conservative, and only if exceeded, is a more comprehensive evaluation required, involving spatial averaging and/or dosimetric modelling, to confirm compliance with ICNIRP basic restrictions (ICNIRP, 2010).

3.2.2. Specific sources

In this Section, the 14 categories that are considered to be most relevant to IF exposure, with at least one (MF and/or EF) EQ > 0.05, are discussed in more detail. The ICNIRP exposure quotients at 20 cm are illustrated in Fig. 6. The highest median EQ_E (0.53) was found for *induction cookers*, although the maximum EQ_E (1.00) was measured for a CFL (median: 0.22). Substantial EQ_H's (all outliers) were found for two *induction cookers*, one *microwave oven with IT*, and one *power tool* (a sanding machine). Furthermore, from the 14 categories, only five had median EQs above the threshold of 5%, albeit in some

Table 3
Categories of IF-field emitting household appliances, with # representing the number of appliances, and n_s the total number of measurement samples if there was a difference (see table footnotes). (AC=alternating current, IT=inverter technology, WLAN=wireless local area network.).

Category	# (n_s)	Category	# (n_s)	Category	# (n_s)
AC adapter	6	electric water boiler	1	portable radio	1
air conditioning (IT)	1	electricity power saver	1	power tool	48
baby monitor	4	exhaust hood	3	radio-controlled (RC) toy	1
battery charger	5	fluorescent lamp	5	refrigerator (IT)	1
blender	7	gaming console	5	refrigerator (non-IT)	2
cold-cathode fluorescent lamp (CCFL)	1	hair drier	5	robot vacuum cleaner	1
compact fluorescent lamp (CFL)	28	hair removal device	5	scanner	1
clock fan	1	hair straightener	1	sewing machine	1
coffee maker	1	halogen lamp	2	solar inverter	1
compressor	1	heat pump	1	spotlight with transformer	5
cathode-ray tube (CRT) display	11	hotplate	2	storage water heater[e]	1 (2)
dehumidifier	2	induction cooker	12	tablet	1
dimmed lamp[c] (non-CFL)	7 (11)	kitchen robot (blender)	1	toy motor	1
dimmer switch[c]	9 (11)	laundry machine[a,b] (IT)	6 (16)	ultraviolet (UV) lamp	1
dishwasher[b]	7 (17)	laundry machine[a,b] (non-IT)	8 (22)	vacuum cleaner[c]	15 (17)
electric bicycle	1	liquid-crystal display (LCD)	5	vaporiser	2
electric heater	1	light-emitting diode (LED) display	1	ventilation system	2
electric massager	1	LED light	3	wake-up light	1
electric meat slicer	1	living light	1	water pump	1
electric piano	1	microwave oven (IT)	5	welding machine[e]	1 (2)
electric toothbrush	2	microwave oven (non-IT)	12	WLAN router	3
electric toothbrush charger[d]	3 (6)	mp3-player	1		

[a] Category includes both tumble driers and washing machines.
[b] Measurements were taken at different times during operating cycles.
[c] Measurements were taken at different power states.
[d] Measurements were taken with and without the toothbrush connected.
[e] Measurements were taken during 'standby' and 'active' modes.

categories there were not many samples. In this Section, any reported EQ refers to EQ_{ICN}.

3.2.2.1. Battery charger. All (five) assessed battery chargers emitted IF fields. Four of them emitted both IF-EF and –MF, with fundamental frequencies f_f between 42 kHz and 65 kHz. For those battery chargers, $E_{peak,\ i}$ of up to 6.4 V/m and $H_{peak,\ i}$ of up to 0.03 A/m were measured at a distance of 20 cm, and one of them had at this distance an EQ_E of 0.35 due to five peaks above the 5% threshold. The fifth battery charger, in its turn, only emitted IF-EF, with a significantly lower E_{peak} at f_f 20 kHz of 0.1 V/m (at 20 cm).

3.2.2.2. Cathode ray tube (CRT) display. Although a fast-disappearing technology, 11 screens using CRT technology were found in the study: eight televisions (TVs), one computer screen, and two videophones. In their EF and MF spectra, f_f of 15.5 kHz (in eight cases; six TVs and two videophones) and 31 kHz (three remaining cases) were observed, with maximum $E_{peak,\ i}$ of 0.2–11 V/m and maximum $H_{peak,\ i}$ of < 0.01–0.38 A/m at 20 cm from the screen. In comparison, Kurokawa et al. (2004) measured maximum H_{peak} between 10 kHz and 150 kHz above 0.40 A/m at 10 cm, and up to 0.26 A/m at 50 cm. Mantiply et al. (1997) further reported root-mean-square (RMS) EF strengths of 0.22–52 V/m and RMS MF strengths of 0.26 mA/m – 0.17 A/m at 30 cm from the screen centre. Finally, at a distance of 20 cm, six CRT displays had a relevant EQ_E of up to 0.43, due to two to six single peaks, including sometimes a number of 50 Hz harmonics between 300 Hz and 5 kHz.

3.2.2.3. Cold-cathode fluorescent lamp (CCFL). Only one CCFL was assessed in this study (EQ_E 0.15 at 20 cm). While the EHP-50 100 kHz measurements indicated a sharp peak in the EF spectrum at f_f 39 kHz, with at this frequency E_{peak} 10.8 V/m at 20 cm, the EHP-200, on the other hand, measured around the same frequency a broad peak comprising two narrow peaks, with $E_{peak,\ i}$ of 5.4 V/m and 6.8 V/m (at 20 cm).

3.2.2.4. Compact fluorescent lamp (CFL). Except in the case of four CFLs with narrow peaks at f_f between 27 kHz and 31 kHz, all CFL EF spectra had broad peaks (typically 6 kHz wide) at f_f between 33 kHz and 62 kHz, with $E_{peak,\ i}$ of up to 25 V/m. In 20 out of 28 samples, relevant EQ_E of up to 1.00 were found at 20 cm (due to one to four peaks, often part of the same broad peak), and in one sample even at 50 cm (EQ_E 0.24). MF were overall negligible in the IF range due to the symmetrical construction of the fluorescent tubes (Nadakuduti et al., 2012) (Table 4). It should be noted that, in this study, the distance to the edge of the lamp was used, which included the lampshade, if there was one.

Previous studies reported E_{peak} exceeding the ICNIRP reference level at distances closer than 20 cm from the lamps (Bakos et al., 2010; Nadakuduti et al., 2012; Van den Bossche et al., 2015), with e.g., E_{peak} of 117 V/m at 5 cm, and 97 V/m at 15 cm (Van den Bossche et al., 2015). Furthermore, at a centre-to-centre distance of 15 cm, EQ_E (calculated using E_R 87 V/m (ICNIRP, 1998), as opposed to 83 V/m in this study) between 0.7 and 5.0 were reported across 11 CFLs by Nadakuduti et al. (2012). However, although the reference levels were exceeded, exposure was found to be below the basic restrictions.

3.2.2.5. Electric toothbrush charger. At both measuring distances, each electric toothbrush charger (#=3) was measured twice (n_s=6); once *with* and once *without* the electric toothbrush placed on the charger. For all three chargers, f_f shifted slightly when removing the toothbrush; once from 22.5 to 21.0 kHz, and twice from 42.2 to 39.5 kHz. Furthermore, in the first case, H_{peak} increased (from 0.09 A/m to 0.14 A/m at 20 cm) while maximum E_{peak} remained the same (4 V/m at 20 cm), and EQ_E was 0.06 at 20 cm. In the two other cases, both EF and MF intensities decreased when removing the toothbrush (at 20 cm: E_{peak} decreased from ~1.1–1.4 V/m to 0.3 – 0.4 V/m, and H_{peak} from ~0.03 to 0.04 A/m to 0.02 A/m), and EQs

Table 4
Summary of the measurements of the categories containing at least one IF-field emitter. Ranges of wideband electric- (E_{wide}) and magnetic-field (H_{wide}) strengths measured at 20 cm and 50 cm in the 100 kHz band (with EHP-50) and characteristics of the observed spectra (last column), with f_f the fundamental frequency (or range of f_f) and N(...) the region in which a heightened field strength without clear f_f was observed (see e.g., Fig. 3b). Frequencies (in kHz) in green indicate electric-field components only, in purple magnetic-field components only, and in ***black and bold*** both.

category	E_{wide} (V/m)		H_{wide} (A/m)		f_f / N(…) (kHz)
	20 cm	50 cm	20 cm	50 cm	
AC adapter	0.66-1.73	0.49-0.68	0.08-0.10	0.07-0.09	58 – 70*
air conditioning (IT)	0.69	0.49	0.03	0.02	21* + N(160-215)
baby monitor	0.37-0.72	0.43	0.02-0.03	0.03	N(1-100) / --
battery charger	0.27-11.56	0.24-3.01	0.02-0.10	0.02-0.11	20 + **42 – 65***
blender	0.55-1.86	0.34-0.67	0.05-0.68	0.02-0.10	N(1-400) + N(1-40)
CCFL	10.75	1.41	0.08	0.08	39*
CFL	1.46-37.27	0.88-15.45	0.02-0.11	0.02-0.10	27 – 62*
clock fan	0.36	0.30	0.03	0.03	**63**
CRT display	0.93-22.81	0.66-6.09	0.09-0.40	0.03-0.12	**N(1-5) + 15.5 + 31***
dimmed lamp (non-CFL)	0.65-11.10	0.44-2.99	0.07-0.11	0.06-0.10	N(1-50)
dimmer switch	0.37-14.94	0.41-3.61	0.02-0.13	0.02-0.10	N(1-50)
dishwasher	0.18-0.61	0.20-0.31	0.01-0.03	0.02-0.03	12 + 16 + 48 + 62 / --
electric massager	6.10	0.46	0.10	0.03	N(1-100) + N(1-20)
electric meat slicer	0.44	0.31	0.04	0.03	N(1-100) + N(1-10)
electric toothbrush charger	0.56-4.26	0.53-1.15	0.07-0.17	0.06-0.09	**21 – 23*** + **39 – 42***
exhaust hood	0.20-0.44	0.16-0.33	0.02-0.04	0.02	20 + 28 / --
fluorescent lamp	6.02-40.15	0.69-15.42	0.03-0.11	0.03-0.09	**35 – 51*** / --
gaming console	0.32-1.97	0.16-0.73	0.02-0.09	0.02-0.03	**32 – 65** / --
hair drier	0.40-0.78	0.26-13.85	0.07-0.18	0.02-0.08	**N(1-20)**
induction cooker	7.62-41.84	2.68-11.81	0.18-3.71	0.03-0.82	**19 – 70***
laundry machine (IT)	0.32-6.21	0.23-1.15	0.02-0.13	0.02-0.10	N(1-400) + 8* + **15*** + 18* + 21* + 30* + 33 – 293
LCD	0.34-42.70	0.25-19.59	0.03-0.72	0.02-0.16	**N(45-90)* + 45 – 67*** / --
LED light	0.32-0.60	0.25-0.30	0.03-0.03	0.02-0.03	N(150-200)*
microwave oven (IT)	0.45-2.47	0.39-0.70	0.29-1.43	0.14-0.28	**N(20-80)***
microwave oven (non-IT)	0.20-0.83	0.21-0.78	0.02-0.29	0.02-0.11	**N(1-50)** / --
mp3-player	0.61	0.30	0.04	0.03	**58**
power tool	0.31-19.78	0.18-14.51	0.03-2.28	0.02-0.22	16* + **N(1-400)**
RC toy	0.61	0.30	0.19	0.03	**N(1-30)**
refrigerator (IT)[a]	13.03	4.39	0.10	0.10	6*
robot vacuum cleaner	0.39	n.m.	0.09	n.m.	**9.5***
scanner	0.90	0.66	0.10	0.08	96
sewing machine	0.99	0.90	0.10	0.09	N(1-75)
spotlight with transformer	0.55-6.91	0.76-2.40	0.06-1.51	0.10	**15*** + N(32-60) + 32 – 46*
storage water heater	0.69-0.70	0.66	0.08	0.08	15 + 51
tablet[a]	0.60	0.58	0.07	0.07	16*
UV lamp	1.36	0.74	0.09	0.09	25
vacuum cleaner	0.41-4.20	0.30-1.52	0.02-0.54	0.02-0.09	**N(1-400)** + 15 – 17*
ventilation system	0.65-1.87	0.68	0.03-0.08	0.07	N(1-50) + 16*
wake-up light	6.52	1.44	0.22	0.09	**27* + N(25-50)***
welding machine	4.21-7.29	0.65-1.78	0.12-0.18	0.08-0.15	**98***
WLAN-Router	0.29-1.00	0.36-0.71	0.02-0.09	0.02	20*

All measurements included were performed with the source not switched off, i.e., 'on' or 'standby'. (n.m. = not measured.)
'*' = 'plus harmonics of this frequency'; '—' = 'fundamental frequencies found within this range'; '/--' = 'or no IF components'.
[a] EHP-200 400 kHz band measurement

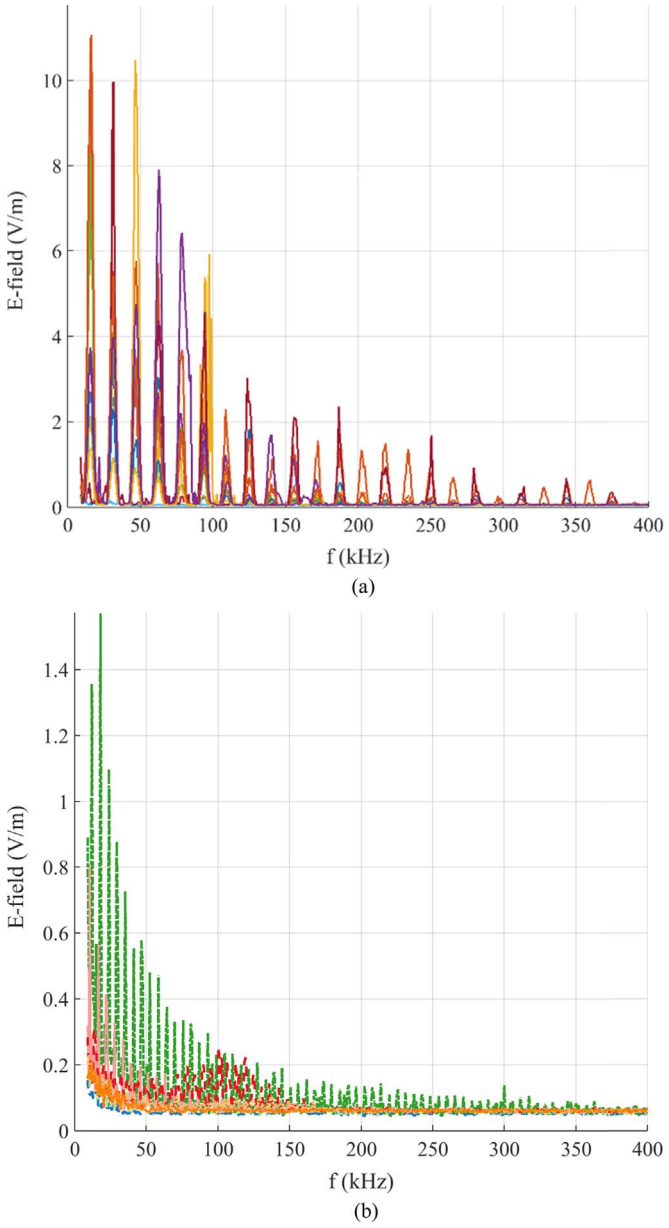

Fig. 3. Examples of intermediate-frequency spectra (electric field) between 9 kHz and 400 kHz: (a) cathode ray tube (CRT) displays, and (b) blenders. All measurements with the appliances 'on' and performed at 20 cm were included.

were below 0.05 for all measurements.

3.2.2.6. Fluorescent lamp. In the EF and MF spectra of three fluorescent lamps, narrow peaks were observed in the IF range at f_f between 35 kHz and 51 kHz, with maximum $E_{peak,\ i}$ between 20 V/m and 35 V/m at 20 cm (at 50 cm: 8.0–13.5 V/m) and $H_{peak,\ max}$ 0.01 to 0.03 A/m. In these cases, the high IF-EF components resulted in EQ_E of 0.24–0.43 at 20 cm, and of 0.09–0.15 at 50 cm. The two other fluorescent lamps were most likely of an older type, containing a conventional ballast (cf. second FL measured by Kurokawa et al. (2004)) and did not emit IF fields. The only previously published measurements of fluorescent (tube) lighting were done by Van den Bossche et al. (2015), who reported f_f of 45–52 kHz, with a maximum E_{peak} of 200 V/m at 15 cm, and by Kurokawa et al. (2004), who reported H_{wide} (between 10 kHz and 150 kHz) of over 0.04 A/m at 10 cm and 0.01 A/m at 50 cm.

3.2.2.7. Induction cooker. Induction cookers emit both IF-EF and -MF. In this study, f_f were found to vary between 19.5 kHz and 70 kHz. In two cases, f_f shifted during the measurement (in one of them, f_f varied between 42 kHz and 70 kHz in-between measurements). At a measuring distance of 20 cm, all twelve of them had the potential to produce considerable IF-EF exposure, with maximum E_{peak} of 4.8 V/m to 41.5 V/m, which resulted in EQ_E between 0.08 and 0.63 (due to one to four single peaks), and for seven cookers still relevant EQ_E at 50 cm of up to 0.13. Moreover, maximum H_{peak} at 20 cm ranged between 0.2 A/m and 2.7 A/m, with two induction cookers generating above-threshold EQ_H of up to 0.13. All induction cookers were assessed with one pot of 2–3 l of water placed on a cooking zone next to the cabinet edge and used at maximum power.

In contrast to other sources of IF fields identified in this study (with the exception of CFLs), detailed research is already available on induction cookers (Christ et al., 2012; Kos et al., 2011; Viellard et al., 2007). Unfortunately, most of these studies focused on MF only. Christ et al. (2012) measured dominant frequency components at ~20 kHz (with harmonics up to 400 kHz) and H_{peak} of 0.16–1.2 A/m at 30 cm for domestic cooktops; Mantiply et al. (1997) also reported fundamental frequencies between 22 and 34 kHz, E ~4.6 V/m and H 0.7–1.6 A/m at 30 cm.

It should be noted that, by using the ICNIRP (2010) MF reference level for the general public (i.e., 21 A/m between 3 kHz and 150 kHz), as opposed to 5 A/m (ICNIRP, 1998), the relevance of the MF exposure here is significantly reduced compared to older studies. In practice, any H_{peak} below 1.05 A/m is not considered in the EQ calculation, which, to put this into context, would mean that 15 out of the 16 induction cookers measured by Christ et al. (2012) would have below-threshold EQ_H at 30 cm, and just under half of the devices at touching distance.

3.2.2.8. Laundry machine with IT. In total, 14 laundry machines (11 washing machines and 3 tumble driers) were assessed: six of them (all washing machines) emitted detectable IF fields and were catalogued under 'laundry machine (IT)' (Table 3). Most of the laundry machines with IT were measured during different stages of a washing/drying cycle (n_s=16). Though f_f and peak field levels often seemed to vary between stages, no clear distinction between the stages was identified. One IT washing machine had an EQ_E of 0.06 at 20 cm due to a maximum E_{peak} of 4.7 V/m at f_f 8 kHz. The other laundry machines emitted much lower fields; one emitted both IF-EF and -MF at f_f 15 kHz (at 20 cm, H_{peak} up to 0.01 A/m and E_{peak} up to 1.4 V/m), one predominantly IF-MF (f_f 30 kHz, H_{peak} up to 0.02 A/m at 20 cm), others solely IF-EF (at f_f of 8 kHz, 18 kHz, 21 kHz, 33 kHz, 74 kHz, 205 kHz, and 293 kHz), with E_{peak} of up to about 0.5 V/m at 20 cm. In comparison, for one tumble drier, between 10 kHz and 150 kHz an H_{peak} of 0.01 A/m was measured by Kurokawa et al. (2004) at 10 cm.

3.2.2.9. Liquid-crystal display (LCD). One LCD-TV did not emit any IF fields. For the other four LCD screens, f_f in the EF and MF spectra were observed at 45 kHz (2 TVs), 57 kHz (laptop), and 67 kHz (TV; only EF).. The difference in f_f can be attributed to the horizontal scan frequency. Furthermore, the LCD-TVs with f_f 45 kHz were most likely CCFL-back- or -edge-lit and had relevant EF exposure at 20 cm (EQ_E=0.29) and 50 cm (EQ_E=0.20). Overall, at 20 cm from the centre of the screen, E_{peak} and H_{peak} ranges were 0.07–23 V/m and < 0.01–0.70 A/m, respectively. In one of the LCD-TVs an additional increase in the EF spectrum between 45 kHz and 90 kHz was observed, which might be due to an automatic brightness adjustment option. Finally, the laptop screen generated a stronger MF (at 57 kHz) relative to its EF strength, compared to the two 45 kHz

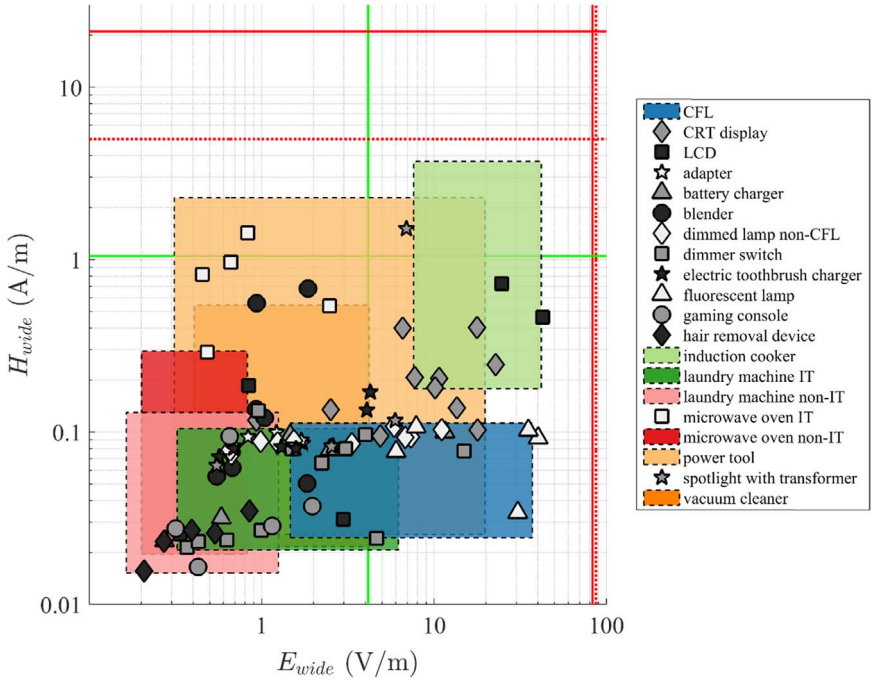

Fig. 4. Wideband electric- (E_{wide}, V/m) vs magnetic-field (H_{wide}, A/m) levels in the 100 kHz band measured at a distance of 20 cm to the source. The red lines are the ICNIRP reference levels (full: ICNIRP, 2010, dotted: ICNIRP, 1998), the green lines are the 5% borders. Shown here are only those categories for which $n_s > 3$ and with at least one appliance with a measured field strength (E_{wide}/H_{wide}) at 20 cm higher than 1% of either ICNIRP (2010) reference level above 3 kHz. Categories for which $n_s > 11$ are represented by areas rather than single points. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

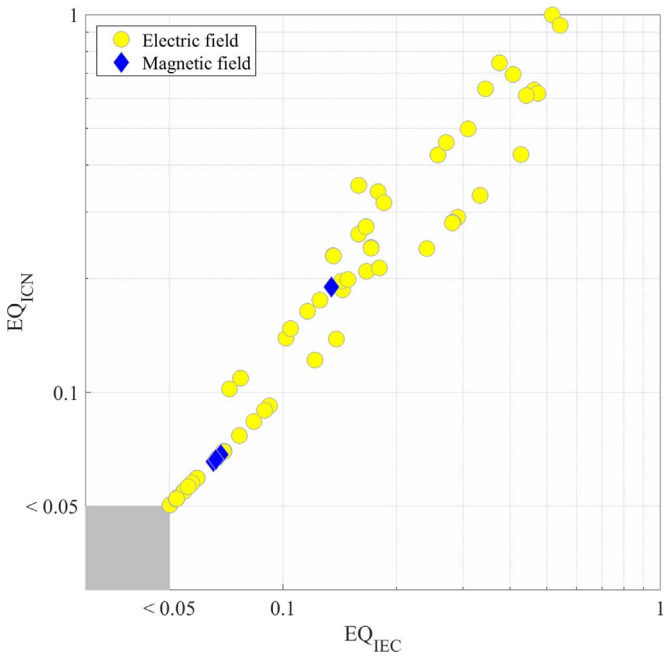

Fig. 5. Electric-field (yellow dots) and magnetic-field (blue diamonds) exposure quotients at 20 cm, calculated using IEC 62233:2005 (x-axis) and ICNIRP guidelines (y-axis). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

TV sets.

3.2.2.10. Microwave oven with IT. Five of the assessed microwave ovens generated IF fields and were categorized under 'microwave oven (IT)' (Table 3). In the MF spectra of microwave ovens with IT, broad peaks were observed between 25 kHz and 40 kHz with maximum H_{peak} of 0.4–0.8 A/m at 20 cm. Based on the EHP-200 400 kHz measurement, one IT microwave oven had at 20 cm an EQ_H of 0.07, due to a maximum H_{peak} of 1.44 A/m at 70 kHz (second harmonic. However, in the EHP-50 100 kHz measurement, the component at this frequency was much lower (0.03 A/m), and the peak was actually observed at the fundamental frequency (0.17 A/m). Moreover, the EF spectra measured with the two probes were also inconsistent. The EHP-200 measured peaks in the 30–50 kHz and 50–80 kHz ranges (and corresponding harmonics) with maximum E_{peak} of 0.60–2.45 V/m, whereas in the EHP-50 measurements, these peaks were usually lower, or not even present.

3.2.2.11. Power tools. The power-tool category is much broader than any other defined in Table 3 and encompasses anything 'large' that is powered by fuel or electricity (mains or battery) and is actively handled by a person (often in the garden). A breakdown of the 48 considered power tools is given in Table 5. Relatively high field values were sometimes measured (Fig. 4), and four power tools had notable EQs: two chainsaws (EQ_E 0.06–0.14), an oscillating sander (EQ_E 0.05), and a sanding machine (EQ_E 0.18 and EQ_H 0.07). The relatively high IF exposure was mainly due to a series of peaks composing capricious spectra both for EF and MF (such as in Fig. 3b), possibly power-frequency harmonics ranging far into the IF range. Only one of the considered power tool appliances had a real fundamental frequency in the IF range (an electric drill with f_f 16 kHz).

It should further be noted that also in the ELF range (data not shown), the emitted fields were sometimes found to be relatively high, i.e., at ~5% of the ICNIRP (2010) reference level for the general public.

3.2.2.12. Refrigerator with IT. A systematic error occurred during the EHP-50 100 kHz measurement while measuring this source, so the fundamental spectral component at 6 kHz was extrapolated from harmonic signals at 12 kHz, 18 kHz, etc. observed in the EHP-200 400 kHz measurement. At 20 cm, a maximum E_{peak} of 11.13 V/m was

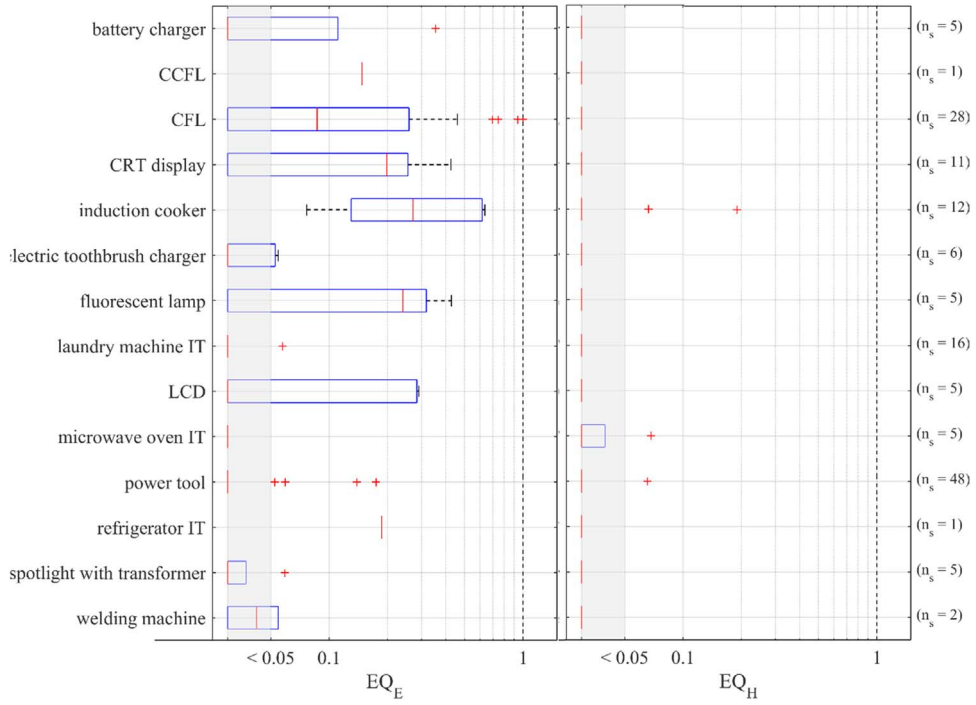

Fig. 6. *Electric-field* (left) and magnetic-field (right) EQ boxplots showing median (red lines) as well as 25th–75th percentile ranges (blue box) at 20 cm calculated following guidelines in ICNIRP (2010) for the relevant categories. All other categories only had EQs < 0.05. EQs in the gray area are < 0.05. (Red crosses are outliers.) n_s=number of samples. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 5
List of power tools (#=number of appliances).

Tool	#	Tool	#	Tool	#
Angle grinder	1	Garden shredder	1	Leaf blower	2
Belt sander	1	Garden tiller	1	Mitre saw	1
Biscuit cutter	1	Garden trimmer	1	Oscillating sander	1
Brush cutter	1	Grinder	2	Planer	1
Chainsaw	5	Hedge trimmer	5	Router	1
Circular saw	1	Jigsaw	4	Sander	4
Electric drill	8	Lawnmower	5	Saw	1

measured at 12 kHz (second harmonic), which resulted in an EQ_E of 0.19.

3.2.2.13. Spotlight with transformer. Based on the spectra of the measured spot-lights-with-transformers, a distinction was made between (a) two magnetic transformers, for which high ELF-MF (H_{peak} at 50 Hz of up to 5.82 A/m at 20 cm) and low ELF-EF (E_{peak} at 50 Hz of up to 4 V/m at 20 cm) were observed, and no IF emissions; (b) three regular electronic transformers with IF-EF emissions at f_f of 32–46 kHz (and corresponding uneven harmonics up to ~250 kHz), of which one had an EQ_E of 0.06 due to a maximum E_{peak} of 4.9 V/m; and (c) one transformer with a *slow-start* circuit, with a 50 Hz EF component of 130 V/m and IF-EF and -MF emissions at an f_f of 15 kHz, but not generating relevant IF exposure.

3.2.2.14. Welding machine. One welding machine – a manual metal arc (MMA) welder – was assessed. On standby (i.e., switched on but not actively welding) an EQ_E of 0.05 was found at 20 cm, due to a peak at f_f 98 kHz, and no MF components were detected. When welding, however, the peaks in the EF spectrum decreased (E_{peak} at 98 kHz was reduced from 4.5 V/m to 2.4 V/m, so the EQ dropped below 0.05) or disappeared (third harmonic), while at the same time, peaks appeared in the MF spectrum at 99 kHz (H_{peak} of 0.12 A/m) and its second harmonic.

3.3. Overall discussion

At a certain distance (> 1 m) from any electric appliance, IF field levels in residences were found to be generally low, with average wideband field strengths between 1 kHz and 100 kHz of approximately 1 V/m and below 0.05 A/m (i.e., the probes' noise floor). Measurements in the middle of the room actually showed only a minor increase in absolute EF strengths (on average (GM) +0.7 V/m, maximum +9.5 V/m) when in maximum living mode as compared to hibernation mode (no IF-MF were measured at a distance of > 1 m from an electric appliance).

At a distance of 20 cm (or closer), however, IF field emissions from certain appliances (especially induction cookers, CRT displays, LCDs, CFLs and other fluorescent lighting, some power tools, and some microwave ovens with IT) can become relevant, i.e., with a total IF-EF or –MF exposure above 5% of the ICNIRP reference levels, using IEC or ICNIRP summation rules. Overall, fundamental frequencies of IF emitting appliances varied between 6 kHz (refrigerator with inverter technology) and 293 kHz (laundry machine with inverter technology) with most somewhere between 20 kHz and 60 kHz. Often, the f_f were accompanied by harmonics (up to 400 kHz for strong emitters such as induction cookers), and sometimes also by regions of 'noisy' elevated field strengths (e.g., spotlights with transformers and some LCD-TVs). However, in some cases, the observed spectra were much noisier and seemed to be dominated by 50 Hz harmonics emanating far in the IF domain (e.g., blenders (Fig. 3b), dimmer switches, and power tools).

3.3.1. Inverter technology

During the study, IF fields were particularly evident in devices using 'inverter technology' (IT). IT is utilised in the design of some microwave ovens, refrigerators, laundry machines, and air conditioning systems, and offers better control (speed or temperature) and a higher

energy efficiency. Due to the presence of IF fields in appliances with IT, the categories *microwave oven*, *refrigerator*, and *laundry machine* were split up (Table 3).

However, the IT did not appear in the measured spectra in the same way for all these appliances. In the case of microwave ovens, for example, broad peaks were observed in both the MF spectrum between 20 kHz and 40 kHz and in the EF spectrum between 20 kHz and 100 kHz. The refrigerator with IT, on the other hand, had an f_f in the EF spectrum at 6 kHz, and the air-conditioning system showed IF-EF emissions at three frequencies (20 kHz, 40 kHz, and 200 kHz). Finally, the spectra of the assessed laundry machines with IT were much more erratic, with EF and (to a lesser degree) MF emissions at f_f between 15 kHz and 293 kHz.

3.3.2. Strengths and limitations

In this study, a wealth of measurement data on EF and MF levels at IF were collected, spanning 42 properties and 279 appliances (65 categories) over three countries. IF exposure-relevant household appliance categories that were not previously described in the literature include power tools, electric toothbrush and battery chargers, LCDs, and appliances with inverter technology. For appliances that have been assessed in previous studies, e.g., induction cookers, CFLs, and CRTs, the measurements here are in line with those reported in those studies. The information provided here fills a gap in knowledge in terms of typical human exposures to IF-EF and -MF, and will be useful, in combination with appliance usage data, in epidemiological studies investigating potential links between (adverse) health effects and exposure to IF fields.

Although this paper compares the field levels at a given distance, it should be emphasised that actual exposure will depend on typical user distance to the appliance (e.g., the use of an LCD-TV or LCD-laptop) and on duration and frequency of use of the appliance. Additionally, the spatial combination of multiple sources (e.g., fluorescent lighting installed above an induction cooker) should be taken into account in any extensive IF exposure assessment.

Moreover, no measurements were performed at closer distance, because, besides becoming more unreliable, their relevance to exposure assessment would be questionable, as the majority of these appliances are unlikely to be used at distances closer than 20 cm.

The possible temporal variation in the emitted fields has not been accounted for in this study, and this could be the cause of the occasional discrepancy between the EHP-50 and EHP-200 measurements. Moreover, for several appliances, no IF emissions were measured above the EHP measurement sensitivity at the distances investigated, even though in all cases, contributions in the 2 kHz to 1 MHz band had been measured with the NFA meter – although possibly at distances closer than 20 cm. The fact that field levels were below the sensitivity of the EHP probes at the distances investigated but not in the NFA-1000 measurements shows how quickly the emitted fields can decay with distance, and show that even though quite a few appliances may have components emitting in the IF range, they would fall to very low levels, below the sensitivity of our measurement equipment at a distance of 20 cm or less.

4. Conclusions

Measurements of electric and magnetic fields at intermediate frequencies (IF) were performed in residences in three countries by way of a common protocol. Typical IF fields in the most frequented rooms were assessed as well as emissions from a wide range of household appliances. At distances of 1 m or more from the IF sources, field levels were found to be generally low. However, use of certain appliances at close distances (20–50cm), including induction cookers, LCD screens, microwave ovens and refrigerators with inverter technology, and (compact) fluorescent lighting, may result in exposures above 5% of public ICNIRP (2010) reference levels. In general, EF and MF emissions of household appliances in the IF range contained either harmonic signals, with fundamental frequencies between 6 and 293 kHz, which were sometimes accompanied by regions in the IF spectrum of rather noisy, elevated field strengths, or much more capricious spectra, seemingly dominated by 50 Hz harmonics emanating far in the IF domain. The maximum peak field strengths recorded in this study were 41.5 V/m and 2.7 A/m (both resulting from induction cookers) and at 20 cm and beyond none of the appliances exceeded the ICNIRP and IEC exposure summation rules (maximum observed electric- and magnetic-field exposure quotients were 1.00 and 0.13, respectively). The results reported here may provide a useful resource for epidemiological studies investigating the potential link between (adverse) health effects and exposure to IF fields.

Funding

The research leading to these results has received funding from the European Community's Seventh Framework Programme (FP7/2007–2013) under Grant agreement no 603794 – the GERONIMO project.

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