Extremely Low Frequency Electric and Magnetic Fields Exposure: Survey of Recent Findings

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***Abstract*—Extremely Low Frequency Electric (ELF-EF) and Magnetic Field (ELF-MF) exposure is caused by different types of sources, from those related to the production, transmission, and distribution of electric currents, to technologies of common use, such as domestic appliances or electric transportation. Establishing the levels of exposure for general public is a fundamental step in the health risk management process but could be challenging due to differences in the approaches used in different studies. The goal of this study is to present an overview of the last years research efforts (from 2015 to nowadays) about ELF-EF and MF exposure in everyday environments, considering different sources and different approaches used to assess the exposure. All ELF-EMF exposure levels were found to be below the ICNIRP guidelines for general public exposure. The higher MF levels were measured in apartments very close to built-in power transformers. Household electrical devices showed high levels of MF exposure in their proximity, but the duration of such exposure is extremely limited.**

***Index Terms*—Dosimetry, extremely low frequency electric fields (ELF-EF), extremely low frequency magnetic fields (ELF-MF), exposure levels assessment, measurements.**

I. Introduction

NOWADAYS, the use of devices based on electromagnetic fields (EMF) is an integral part of everyday life [1], [2]. Focusing on the exposure to extremely low frequency (ELF) electric and magnetic fields, which occupy the lower part of the electromagnetic spectrum in the frequency range 0–3000 Hz, the primary sources, besides natural EMF sources are caused by human activities and are related to the production, transmission, distribution, and use of electric currents. In outdoor environments, concerns about possible adverse health effects of extremely low frequency (50–60 Hz) electric and magnetic fields (ELF-EMF) have therefore focused on the exposure due to high voltage power lines, operating at various voltages between 110 up to 1150 kV, depending on the country but there are many other potential sources: built-in transformers, substations and underground cables, required for the supply and distributions of household electricity can be influential on the exposure levels, especially when placed in close proximity to residential areas or buildings [3], [4]. Moreover, due to the rapid evolution of technology in the last years, and the advent and wide spreading of new technological paradigms such as the electric transportation (see, e.g., [5]), both private and public, the shift to new energy distribution systems (see, e.g., [6]), such as the smart grids, and the increasing use of technologies for using renewable energy sources, such as photovoltaic or wind power facilities (see, e.g., [7]), new ELF-EMF exposure scenarios are emerging. In indoor environments, electrical appliances in use at homes, schools and offices represent the major contributions to ELF-EMF exposure, and their number, type and position with respect to the human body could play a key role in the exposure levels [8], as the highest magnetic flux densities to which most people are exposed in the home arise close to domestic appliances and decrease rapidly with distance from these appliances [9]. The number of electrical appliances in households is continuously increasing, in fact, the study of Schüz et al. [10] suggested that up to one-third of total exposure to ELF-MF should be attributed to personal appliance uses and the evaluation of their contribution to ELF-EMF exposure is becoming particularly relevant. Moreover, also household appliances emitting in the intermediate frequency range (IF, 300 Hz-1 MHz) such as compact fluorescent lamps (energy-saving light bulbs) and induction cookers, are becoming more commonplace and has grown significantly in recent years [9], [11], [12].

In light of this, in 2001, the International Agency for Research on Cancer (IARC) classified exposure to extremely low frequency electric fields (ELF-EF) as "not classifiable as to their carcinogenicity" (group 3), while extremely low frequency magnetic fields (ELF-MF) were classified as "possibly carcinogenic to humans" (group 2B) based on "limited evidence of carcinogenicity in humans" and "inadequate evidence of carcinogenicity in experimental animals" [2]. This assessment has been further confirmed by the European Commission's Scientific Committee on Emerging and Newly Identified Health Risks (SCENIHR) [13]. This is particularly relevant for children exposure, since a possible correlation between ELF-MF exposures and childhood leukemia was hypothesized, with an increase of risk for time-average magnetic flux densities above 0.3–0.4 μT. However, the cause of this possible correlation is still

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uncertain [14], and long-term time-average exposures exceeding 0.3–0.4 μT are not common in residential environments [15].

In addition to childhood leukemia, various possible other adverse health outcomes have been investigated including reproductive health effects (see, e.g., [16]), Alzheimer's disease (see, e.g., [17]), adult leukemia and brain tumors (see, e.g., [18]), and lymphomas (see, e.g., [19]). Despite all these efforts, the potential causality of the ELF-MF for adverse health effects is completely unclear and a generally accepted mechanism for biological effects at low environmental levels of ELF-MF is still lacking. Nevertheless, rigorous health risk analysis, needed for assuring the proper management of the public health towards the exposure to ELF-EMF, is a still ongoing process, and requires an accurate knowledge of the levels of exposure to ELF-EMF in everyday living scenarios.

To the best of our knowledge, the last summarizing paper, aimed at collecting and reviewing main findings about ELF-EMF exposure levels, was published by Gajšek and colleagues in 2016 [9]. Due to the advent of new technologies, and thanks to the refinement of the strategies for exposure assessment, many other studies have been published after the previous review [9].

In this survey, we aim at summarizing ELF-EMF exposure findings by collecting and reviewing research efforts done in the last years and not included in the previous review [9], from 2015 to nowadays. In fact, numerous studies were carried out in the last years focusing on rigorous exposure assessment to ELF-EMF, using different approaches e.g., environmental or personal measurements, computational electromagnetics techniques. The majority of studies focused at investigating the levels of ELF-EMF exposure in particular for the children (see, e.g., [20], [21]) and for pregnant women and their possible impacts on fetal growth (see, e.g., [22]), while few studies focusing on adults exposure levels were found [23], [24]. Regarding the exposure scenario, the studies focused at investigating the exposure in relevant micro-environments, both indoor and outdoor (see, e.g., [25]), taking account other environmental factors, such as the degree of urbanization of the environment under exam, (e.g., rural, suburban, urban), the population density in urban area, the distance from power lines, transformers and substations, the time spent during day time on public transport or in the cars [20], [26]. Since the interest in children category, we found also that the public places more investigated in literature were schools, park and kindergarten [27]. Since in [9], the authors stated that "The reference levels for exposure of the general public might be exceeded in the immediate vicinity of such devices", we decided to include in this review also studies about exposure measurements of domestic devices emitting in the IF range, since their use has recently increased in commonplaces [9], [11], [12]. The ELF-EMF exposure levels found in literature have been then summarized, highlighting research gaps regarding new technologies and incoming exposure scenarios.

II. Methods

This review included literature studies, which are focused on general public ELF-EMF exposure assessment and were published after the last review on ELF-EMF exposure assessment [9]. A literature search of research studies published between 2015 and 2022, was performed using Scopus database. The search terms were derived as a combination of the various ways of describing the exposure characteristics of ELF EMF (e.g., extremely low frequency magnetic field, extremely low frequency electric field, ELF-MF, ELF-EF, electromagnetic field, low frequency field, etc.), the exposed subjects (e.g., fetus, children, adolescent, pregnant women, adults, etc.), the environment (e.g., indoor, residential, school, home, outdoor, park, etc.), the type of sources (e.g., power lines, near field sources, domestic appliances, electronic devices, household appliances, IF household appliances, etc.) and the exposure assessment methods (e.g., exposure assessment, exposure measurement, dosimetry, exposure personal measurements, exposure spot measurements, stochastic dosimetry, etc.). Only articles published in peer reviewed journals and in the English language were evaluated and in the end a total of 51 articles were included in the current review [28].

The selection and data extraction of the 51 articles was done by a working group of experts in the sector. For sake of clarity, it was decided to divide the 51 papers and to summarize the results based on the different exposure assessment method and following metrics comparable with the ICNIRP guidelines [29], as described in the following paragraphs.

III. Exposure Assessment Strategies and Metrics

Different approaches were used to quantify ELF-EMF exposure levels. The traditional techniques involve (i) spot and long-term measurements for evaluating indoor and/or outdoor field levels or fields generated by specific electric devices or household appliances; (ii) personal (or individual) exposure measurements in close proximity to the human body by means of a portable device; (iii) computational methods for dose monitoring the induced electric field in tissues and organs due to specific ELF sources. Furthermore, stochastic and machine learning techniques were recently applied on collected measurements or coupled with computational methods, to evaluate the variability of the low frequency (LF) exposure scenario and the factors that could impact greatly on the exposure levels [30], [31], [32], [33]. Details of the different techniques are reported in the followings.

A. Long-Term and Spot Measurements

For monitoring environmental exposure in outdoor and/or indoor scenarios, field levels are usually recorded by means of broadband antennas, to estimate the aggregated exposure levels generated by all the sources in the LF range, or by narrow band measurements, for assessing the contribution of a single source. The limit of these spot and long-term measurements is that they do not bring information about daily personal exposure, as it depends on the time people spend in a specific environment and on the subject activities [34]. One critical point in comparing results obtained in different studies is that measurements protocols are often completely different. The probe types, the locations and heights of the measurement instruments in the rooms, the distance from indoor sources, the collected data sampling and the duration of the registrations are indeed parameters known to significant influence the estimation of the levels of exposure and can greatly differ from a study to another [30].

As to outdoor environments, spot measurements were mostly carried out at fixed distances from power lines, at fixed locations in different urban or suburban areas and in transport scenarios [35], [36], [37], [38].

In indoor environments, measurements were recorded primarily in locations where residents spend most of their time, such as on bedrooms, kitchen and lounges [25], [39]. Also ELF-EMF indoor measurements in schools and kindergarten were assessed, since the interest in evaluating specifically the children exposure levels [27], [40], [41]. Moreover, to evaluate the contribution of different domestic appliances, different ways were implemented in the literature studies: turning off and on the different electric devices or putting the measurements instruments at the surface of appliances and/or in proximity to ELF-EMF sources [11], [36], [42], [43].

B. Personal Exposure Measurements

Personal exposure monitoring allows to measure the magnetic fields in close proximity to the human body by means of portable devices (i.e., personal exposimeters). In this way, it is possible to include and to register all the ELF-MF contributions in real exposure scenarios both for indoor and outdoor environments. Moreover, to take into consideration the behaviors and the activities of each subject, usually the data are also complemented with GPS data, a questionnaire about subjects' lifestyle at home, and a detailed timetable list about daily activities, their time and their location. The limitations of personal exposure measurements assessment remain in the cost of these measurements campaign and on selecting the correct representative population sample [30].

Various protocols described in literature focused on population categories: from the elderly, adults and adolescent to young children, infants and pregnant women [20], [22], [23], [24], [26], [44]. In most of the studies also information about the location of the subject residence and its levels of urbanization and distance or proximity to electric networks were reported. Commonly used personal dosimeters are the EMDEX II meter or EMDEX Lite meter (Enertech Consultants, Campbell, CA, USA). These two meters guarantee broadband frequency range 40–800 Hz and harmonic frequency range 100–800 Hz measurements, with a sensitivity range from 0.01 to 300 μT. Most described protocols collected measurements for at least 24 h, with a sampling rate varying from 1.5 s to 30 s, by wearing the meter during daytime, whereas, during the night, the meter was supposed to be set near bed but avoiding the proximity to ELF-MF sources (e.g., alarm clocks), to reduce any possible confounding measurements.

Complementary, recently stochastic dosimetry approaches and artificial intelligence methods, such as unsupervised machine learning, were successfully applied to EMF exposure assessment for exploratory data mining to understand possible relationships within the data arising from measurements campaigns. The advantage of using these types of approaches is that they do not require any knowledge about data, and do not assume any linear or non-linear parametric model. The use of stochastic and machine learning approaches to problems related to EMF exposure is very recent but seems promising for characterizing the exposure levels and the factors that could influence this exposure, with example of application in the prediction of radiofrequency (RF) radiation effect on plants [45], in the prediction of wireless local-area network (LAN) EMF in the indoor environment [46] and in the characterization of ELF exposure scenarios in children [33], [47].

C. Computational Modeling and Dose Assessment

The number of dosimetric studies that deals with the evaluation of the induced electric fields in organs and tissues caused by a specific sources or external EM field levels is growing, since the computational electromagnetic techniques have been enormously improved in recent years thank to the advances in high-performance calculation [30]. The solutions are obtained directly solving the Maxwell's equation using commercial or custom-made codes optimized for EM fields at low frequency range. In parallel, the improvements in medical imaging allowed to acquire computable human models with high-number and high-resolution tissues. As an example, the "Virtual Population" family by IT'IS foundation represents an optimal possibility of high-resolution whole-body computational models [48], [49]. The development of always more accurate strategies for solving the electromagnetic problem (see, e.g., [50]), to avoid underestimation of dose for localized exposures [51], [52], or to perform accurate numerical dosimetry starting from data coming from measurements [53] is an open research field. However, despite the progress in high performance computing, the limit of deterministic computational methods is that they still require highly time-consuming simulations. For this reason, their applicability is often limited on the assessment of the compliance to exposure guidelines considering only few specific exposure scenarios (usually the worst-cases), providing no information about how the exposure could change in realistic and highly variable scenarios. A solution to face the variability and uncertainty that characterize the realistic exposure scenarios is obtained also in this case using stochastic methods and machine learning techniques [31], [32], [33]. Indeed, starting from a set of observations obtained from computational methods, stochastic dosimetry allows to build surrogate models, which presents statistical properties similar with respect to the original model, and thus can substitute it, calculating the quantity of interest with a parsimonious computational cost comparing to deterministic methods. These stochastic methods were recently applied both at ELF and RF ranges and allowed to take into account a high number of exposure configurations and to identify the factors that characterize the variability of real EMF scenarios (e.g., the relative position between the source(s) and the subject(s), the polarization of the EMF, or the tissue dielectric properties) [31], [32].

D. Exposure Metrics

Exposure levels reported in the studies based on spot and long measurements and personal exposimeter followed metrics described in the definition of the reference levels reported in

TABLE I
REFERENCE LEVELS OF ICNIRP GUIDELINES FOR GENERAL PUBLIC

Frequency range	*E [kV/m]*	*H [A/m]*	*B [T]*
1 Hz–8 Hz	5	$3.2 \times 10^4/f^2$	$4 \times 10^{-2}/f^2$
8 Hz–25 Hz	5	$4 \times 10^3/f$	$5 \times 10^{-3}/f$
25 Hz–50 Hz	5	1.6×10^2	2×10^{-4}
50 Hz–400 Hz	$2.5 \times 10^2/f$	1.6×10^2	2×10^{-4}
400 Hz–3 kHz	$2.5 \times 10^2/f$	$6.4 \times 10^4/f$	$8 \times 10^{-2}/f$
3 kHz–10 MHz	8.3×10^{-2}	21	2.7×10^{-5}

Notes: f is frequency in Hz.

Table I of ICNIRP guidelines [29]. As to the units of measure, the strength of the electric field (E) was usually reported in units of volts per meter (V/m) and the strength of the magnetic field (H) in units of amperes per meter (A/m). This latter was sometimes expressed in terms of magnetic flux density (B) measured in units of tesla (T) or micro tesla (μT), or in gauss (G) or milligauss (mG). To directly compare the levels of exposure observed in different studies, all the magnetic fields reported in mG were converted to μT, where 1 mG is equivalent to 0.1 μT. The EF and MF values in spot and long measurements and personal exposimeter were usually described in terms of maximum, mean, geometric mean (GM), arithmetic mean (AM) and time weighted average (TWA) quantities, depending on the study under examination.

Regarding dose monitoring in internal tissues, the studies reported as quantity for assessing the exposure levels the induced electric fields, measurements in units of volts per meter (V/m). Usually, the 99th percentile value of the induced electric field (E^{99}) was the relevant quantity reported in the literature studies to be compared with the basic restriction of ICNIRP guidelines [29]. The E^{99} was commonly evaluated for the central nervous system (CNS, 99th percentile induced field indicated as $E^{99}{}_{\mathrm{CNS}}$) and the peripheral nervous system (PNS, 99th percentile induced field indicated as $E^{99}{}_{\mathrm{PNS}}$).

IV. RESULTS

The results about the recent findings on ELF-EMF exposure are divided based on the exposure assessment strategies and following metrics reported in the previous paragraph.

For sake of clarity, details of the subdivision and of the reported literature papers can be found in Table II.

A. Long-Term and Spot Measurements

1) Outdoor Power Lines Exposure: The ELF EMFs levels of the power lines and transformers have been extensively studied in literature, as reported in [9]. Typically, a transmission line's EMF contribution to the ambient disappears at distance greater than 100 m to the lines [54]. The impact of power supply distribution and power lines in the dwellings at least 60 m apart is equal to background magnetic fields, usually around 0.1 µT, and background electric fields up to 20 V/m [34]. However, we found some recent studies, mostly conducted in developing country with growing and expanding cities, that aimed in characterizing the exposure in proximity to power lines.

TABLE II
SUMMARY OF COLLECTED PAPERS ON LF-EMF EXPOSURE

	Scenario	**References**
Long-Term and Spot measurements	Outdoor Power Lines Exposure	[35], [37], [55], [56],
	Transport Exposure	[5], [38], [57], [58]
	Children Exposure in Public Environments	[27], [40], [41], [59], [60]
	Residential Exposure	[11], [25], [36], [39], [43], [59], [61], [62], [63], [64], [65]
	Subjects	**References**
Personal Exposure Measurements	Children/ Adolescents	[20], [21], [26], [33], [44], [47], [66], [67]
	Pregnant Women	[22]
	Adults	[23], [24]
	Source	**References**
Computational modeling and dose assessment	Power Lines	[68], [69]
	Uniform Magnetic Fields	[70], [71], [72], [73], [74], [75], [76], [77], [78], [79], [80]
	Near-Field Sources	[81], [82], [83], [84]

In [55], the study was focused on the ELF-MF radiated from 132/275 kV overhead power lines installed in Malaysia. The measurements were taken at 1 m above the ground level, using an EMDEX II exposure meter. The highest exposure levels obtained were around 0.4 μT (i.e., 4 mG) and the conclusions suggested to keep a safe distance from overhead power lines, for minimizing the exposure to ELF-MF radiation and for reducing the risk of adverse health effects.

In the study [37] conducted in Annaba city, Algeria, the effects of ELF-EMF due to a circuit of two 220-kV lines have been assessed to evaluate possible health effects of the workers and people living in proximity of these substations. The measurements were conducted by the calibrated EMF meter PMM8053B (Narda Safety Test Solutions) in the free space under the high voltage lines, following the IEEE standards [56], at the height of 0, 1, 1.5 and 1.8 m, where the sensitive's parts as organs and major functions (head, heart, pelvis and feet) of the human body are located. The conclusions of the study reported that the EF strengths are significantly higher under two power lines compared to a single power line, with EF amplitude at the height of 1 m at the center of each of the two pilons equal to 1764.24 V/m and 1748.65 V/m, respectively. The maximum value equal to 3198.46 V/m was measured at the middle position of the structure. Also for the MF strengths, the circuit of two 220-kV power lines with great power generates higher levels (almost equal to 2.6 μT), than the single 220-kV power line (almost equal to 0.2 μT).

In [35] the assessment of the ELF-MF exposure levels was conducted for the residential areas in Mangaung metropolitan municipality, South Africa. Specifically, a total of 30 distribution substations (132 kV) and of 30 residential sites near these substations were randomly selected. The measurements were collected at four different corners inside substations and at the distances of 3 m, 6 m and 9 m outside electrical substations, using a Trifield meter model XE 100 (frequency3 to 3000 Hz) at 1 m height. The study highlighted that the ELF-MF decreased rapidly with an increased distance from the substation, passing from a mean value equal to 0.62 μT at 0 m to 0.16 μT at 9 m, suggesting that the residence positions in near proximity of substations should be further monitored.

Also the study [56] dealt with the investigation of the levels of ELF-MF and ELF-EF originated from overhead power lines, selecting 40 randomly HV power lines and HV transformers in different areas inside the Ramallah city, Palestine. Spot measurements were performed using the Spectrum Analyzer NF-5035 at 1 m above ground level to record fields intensities over 6-min period. The measurements data highlighted that the EF levels were dependent on the line's category under investigation (i.e., power line, transformer or distributor), with a minimum mean EF amplitude equal to 3.9 V/m measured under a distributor line, and a maximum value equal to 769.4 V/m measured under a high-voltage power line (66 kV). MF levels showed minimum and maximum values equal to 0.89 and 3.5 μT, respectively.

All the results about the exposure levels described in the previous reported studies were well below ICNIRP guidelines recommended for general public exposures [29].

2) Transport Exposure: Few recent studies focused on ELF-EMF exposure levels in and around transport systems such as trains, metro and emerging hybrid and electric vehicles.

In [38] ELF-MF exposure was assessed in a Finnish metro station, using MF meter MFM 3000 to collect measurements in 17 cases at 1 m height and 4.3 m from the conductor rail, when the trains were leaving the platform. The maximum measured value varied from 0.52 μT to 5.4 μT, staying at high levels for a very short time after the metro train left the platform.

Another study conducted in Theran [57] used the TES-1394 (Electrical Electronic Corp) triaxial device meter for evaluating the ELF-MF levels on intercity and metro trains. Results showed maximum values ranging between 7.9 μT and 1.87 μT, measured in AC and DC trains, respectively.

Different studies dealt with the monitoring of ELF-EMF in electric vehicles and electric urban transports [5], [58]. In [5], MF measurements were collected inside various types of electric vehicles (trams, buses, car) using EFA-300 (Narda Safety Test Solutions) and EMDEX II exposimeter (Enertech Consultans, Campbell, CA, USA). The highest exposure levels were found in the vicinity of direct current (DC) charging installations, with ELF-MF up to 100 μT, and inside the electric vehicles with values up to 30 μT near the internal electrical equipment.

Also the study [58] dealt with the long-term monitoring of ELF-MFs in three electric vehicles over a period of two years, using SEM-600 meters (Safetytech, Beijing, China) positioned on the front and rear seats. Results generally fell in the range of about several tenths of μT, in line with [5].

3) Children Exposure in Public Environments: Since schools, parks and playgrounds are significant places for children, where they spend most of their daytime, recent literature studies were focused on evaluating the ELF MF exposure assessment in this specific type of micro-environments. In [59] ELF and IF fields were measured in the context of Spanish INMA project in 26 schools and their playgrounds and 105 parks, using EHP-50D electric field and magnetic flux density isotropic probe and NBM-550 Broadband Field Meter Basic Unit (Narda Safety Test Solutions). The highest exposure values were found in parks, with mean and maximum values equal to 0.018 and 0.117 μT, respectively, followed by levels measured in school classroom (mean 0.017 μT, maximum 0.1 μT) and in school playground (mean 0.015 μT, maximum 0.035 μT).

In [41] ELF MF levels were measured in playground facilities in Greece, grouping the data based on two environment types, urban and suburban. The measures were collected by EFA-3 and EFA-300 portable field analyzer system (Narda Safety Test Solutions) and revealed no differentiation between urban and suburban environments, with median values equal to 0.144 μT for urban areas and 0.140 μT for suburban ones.

Also in [40] the aim was to estimate the mean value of ELF-MF exposure in 243 Greek schools, situated both far from and near to the main sources (i.e., power lines, transmission grid and substations). Measurements were taken on the perimeters of school buildings, with an EHP-50F three-axial isotropic portable analyzer and a NBM 550 field meter (Narda Safety Test Solutions), considering frequency bands from 1 Hz to 400 kHz. Data were analyzed using the Weighted Peak Method (WPM) and showed an ELF-MF mean value equal to 0.21 μT. A statistically significant difference between mean ELF-MF values in schools placed in urban and semi-urban areas was observed.

In [27] ELF-MFs levels were assessed in five different classrooms at four schools in Korea during digital learning class hours, using an EMDEX II field analyzer. Data were collected for each student and teacher seat at four separation distances (0, 10, 20, 50 cm) from the computer monitor and at seven different points in the classrooms considering three different heights (50, 100, and 150 cm). The highest exposure value was found to be equal to 0.28 μT, while the maximum average exposure value was equal to 0.091 ± 0.025 μT. The highest levels were found near electronic devices and electric distribution boxes.

Finally, in [60] ELF-MF exposure levels were assessed in 60 classroom of three schools located in Bangkok, Thailand. Spot measurements were collected by an EFA-300 Field Analyzer (Narda Safety Test Solutions), performing measurements at five points in each classroom at 1 m height, with an average measurements time of 6 min. Results showed maximum and mean values equal to 0.42 μT and 0.11 ± 0.10 μT, respectively, and highlighted that the main sources of ELF MFs were electrical equipment and electrical wiring, at the working frequency of 50 Hz.

4) Residential Exposure: Most of the considered studies collected spot and long measurements inside or in near proximity of homes, dwellings and buildings, where the presence of near field sources and domestic appliances was also evaluated.

In [59] the indoor exposure levels of 104 houses were collected in Spanish INMA project, showing that the highest ELF-MF exposure was 0.145 μT in one home and that the ELF-IF mean exposure levels ranged from 0.013 to 0.03 μT across the different settings and frequency ranges.

Always in Spain, a systematic campaign of ELF-MF measurements caused by internal transformer stations (TS) in residential building was carried out [25]. Data were collected by the EFA-300 Field Analyzer (Narda Safety Test Solutions), measuring the levels in different rooms of flats near internal transformers. Results highlighted that old TSs usually provide the highest peak exposure levels, with an average value of 0.4 μT for the dwellings above or adjacent to the TSs. The authors stated that one quarter of the population living in proximity of a TS would be exposed to a weighted MF level greater than 0.3 μT.

In Australia, the exposure levels of different houses and their domestic appliances were assessed thanks to EMDEX II triaxial devices [39], [61]: results showed that average exposure levels in all rooms, away from electrical appliances, were equal to 0.03–0.139 μT (0.30–1.39 mG). Indeed, the average GM magnetic field values in various environments were: 0.085 μT (0.85 mG) in beds, 0.139 μT (1.39 mG) in bedrooms, 0.039 μT (0.39 mG) in baby cot, 0.047 μT (0.47 mG) in children's play area and 0.03 μT (0.3 mG) in family rooms. Furthermore, the study highlighted that the highest exposure in residential situations occurred in proximity to appliances, especially microwave ovens, conductive water pipes, meter boxes, and wiring. In [61] the data showed similar behavior, with GM value equal to 0.05 μT in bedrooms and living room, and the highest GM value obtained for front gate (0.11 μT), since these areas are generally closest to the distribution lines. In [62] in Tehran, Iran, 102 houses were selected and the ELF magnetic field levels were measured by TES-1393 EMF tester (SAENCO). Spot measurements were done in three different rooms including kitchen, living room, and bedroom of each residence. The average value of measurements taken in dwellings was 0.1 μT, with non-significant differences found in measurements collected in the different type of rooms.

In Greece, the indoor EMF intensity values and the peaks that might occur were identified in [63], by the Aaronia spectrum analyzer. The mean values of the ELF-MF varied between 0.14 and 0.06 μT, depending on the Greek region under investigation.

In [64] the trend of the EMF exposure levels in Austrian households from 2006 to 2012 was evaluated, by ELF-EF spot measurements during daytime and ELF-MF recordings during nighttime. The ELF-EF were assessed in nine different positions near beds, by isotropic measurement of EF without ground reference (3D-EFM, ROM-elektronik, Deisenhausen, Germany), whereas the short terms ELF-MF ranging from 50 to 2000 Hz were assessed at the nine positions thanks to three-dimensional field probe (Mlog 3D, Merkel, Maintal, Germany). Results showed that the median of the ELF-EFs decreased from 23.20 V/m in 2006 to 13.90 V/m in 2012. The same trend was found in the median of all-night measurements of ELF-MFs, which decreased from 13.50 to 11.37 nT, respectively.

In [36] the residential exposure in the city of Ramallah, Palestine were assessed, by Spectrum Analyzer NF-5035 from Aaronia. To evaluate the contribution on the exposure levels due to domestic appliances, two different power use were considered; first, the home switchboard was turned off, for recording only the background of ELF fields; then, most of the household appliances were instead turned on. The ELF-MF showed GM and geometric standard deviation equal to 0.04 μT and 3.14 μT, respectively. Furthermore, appliances caused maximum mean ELF-EF value equal 67.4 V/m from hair dryer, and maximum mean ELF-MF value equal to 13.7 μT from microwave oven. Also in [43], the contributions on the exposure levels from household appliances were evaluated in 15 homes in regions, showing that the average EF strength measured when the electric devices are switched on is much greater than when they are switched off (maximum values equal to 78 V/m or 24 V/m, respectively).

Finally, we found two recent studies that investigated both EF and MF emitted by different intermediate frequency (IF) sources [11], [65]. In [65], it was underlined that for most of these sources, the EF is the dominating quantity, and that ICNIRP reference levels are exceeded for touchscreens (44 kHz: up to 155.7 V/m at 5 cm), energy-saving bulbs (38–52 kHz: up to 117.3 V/m), fluorescent lamps (52 kHz: up to 471 V/m at 5 cm). Instead, in [11], the maximum peak EF strength was 41.5 V/m recorded at 20 cm from induction cookers and none of the IF exposure levels exceeded the exposure summation rule recommended by ICNIRP guidelines at 20 cm and beyond.

B. Personal Exposure Measurements

In [44] ELF MF exposure levels of 84 adolescents were assessed thanks to the 24h measurements carried by EMDEX II meter attached to their body. Their activities and the microenvironments where they have spent time (i.e., dwellings, school, other indoor environments, transportation, public areas, etc.) were documented by a time-activity logbook. Results reported the TWA levels for daily measurements and for each microenvironments measurements, the percent of time spend above three cut off points (i.e., above 0.2, 0.4 and 1.0 µT) and, at last, the peaks obtained during the monitoring period. The conclusions reported that the ELF MF exposure of adolescents in Israel was in line with the measurements obtained in other countries [9], [20] with values below 0.1 μT for most of the subjects. The GM of the daily TWA was 0.059 μT for all the participants, whereas the AM was 0.073 μT, 23% higher than the GM. The outdoor exposure was higher than the indoor ones and the lowest exposure levels were obtained in schools, with GM equal to 0.033 μT.

In [21] the ELF MF levels were measured by EMDEX II meter worn by 21 children (16 male and 5 female) under the age of 17 years old from different Slovenian regions. The levels of exposure showed high variability between the children, with a variation in the peaks of magnetic flux density from 0.86 up to 139 µT. These peaks did not reflect real ELF MF exposure, as suggested by the authors, as they were measured in proximity of domestic appliances (hairdryer, cooktops, transformer, etc..) turned on only for a very short period of time. Indeed, the average value of all the collected measurements was equal to 0.29 µT, very low compared with the reference levels reported in the ICNIRP guidelines, but rather high compared to the other personal measurements studies here reported. This can be explained by the fact that 6 of the 21 children lived in close proximity to a TS or a high-voltage power line, which can cause higher ELF MF levels [20], [26], [66].

In the contest of the European ARIMMORA project, two studies [26], [66] aimed at collecting the measurements of ELF-EMF exposure for 172 children, with age between 5 and 13 years old, in Switzerland and in Italy using personal exposimeters and by 24h measurements in children bedroom. Measurements have been performed twice, in both summer and winter. Furthermore, the study population was not randomly chosen, but children with potentially higher exposure were oversampled. Children were divided in three study group: in the first group was made of children living or attending a school within 200 m of an overhead high voltage power line at 50 Hz (from 132 kV to 380 kV) or within 50 m of a high voltage underground cable (220 kV), the second group was made of children living in a building with a built-in transformer station, or at least with the transformer attached to a wall of the building, while the third group encloses all the children who do not satisfy the conditions for the first two groups. Results in [26] highlighted that the GM of ELF-MF exposure was equal to 0.04 μT for personal measurements and to 0.05 μT for bedroom measurements. Furthermore, interestingly, the dwellings positions near within 100 m of a highest voltage power line can increase the personal exposure by a factor of 3.3 and the bedroom measurements by a factor of 6.8 respect to dwellings far away from power lines. Results obtained in [66] on exposure levels of children living in the city of Milan, Italy, showed that the GM values over 24 h personal measurements were ranging from 20 to 80 nT, (well below the value of 0.4 µT indicated as possible risk threshold). Seasonal variations seemed not influence the ELF MF exposure and the highest exposure levels were observed at home, during day or in outdoors environments.

Similar analyses were carried out in the EXPERS project, which aimed to assess the personal exposure to ELF MF at a national scale for the whole population, considering both children and adult categories [20], [24]. Measurements were collected in cold seasons by using the EMDEX meter wore over 24h by the subjects in daytime and at a distance of 50 cm to any electric appliances during nighttime. Each subject filled a questionnaire about him/herself and his/her home and a timetable with details about his/her activities during the measurement period. The first study [20], was focused on the results obtained for the children category, collecting the 24h personal measurements of 977 French children. The AM and the GM were equal to 0.09 µT and 0.02 µT, respectively. Furthermore, the proportion of children with a 24h AM higher than 0.4 μT was 3.1%, when considering all children and 0.8%, when excluding alarm clocks, that greatly influence the exposure levels at night. The presence of the high voltage power line in proximity to the homes could also increase the exposure levels, although an exposure higher than 0.4 μT is not reached. Similar results were obtained in [24] for 1046 French adults involved in 24h personal measurements. The AM and GM values were slightly higher than children's values, equal to 0.14 μT and 0.03 μT, respectively. The proportion of adults with a 24h AM higher than 1 μT was 2.1% for all adults and 0.3% for adults for which no alarm clock was identified. The home proximity to a high voltage power line increased the exposure levels.

Data collected thanks to the ARIMMORA and EXPERS projects were further analyzed by means of stochastic and machine learning techniques, for identifying the factors that could influence most the ELF children exposure levels [33], [47], [67]. These studies suggested that factors such as children's age, location of power lines, transformers and substations, and urbanizations levels could influence the total exposure levels of each subject.

In [23] ELF-MF exposure levels of 99 adults in Amsterdam were evaluated, to investigate the association between the exposure and the onset of non-specific physical symptoms. The study population was balanced on demographic features such as sex, age, social economic status, employment, type of house and residential area and the measurements were collected by EMDEX Lite meter worn on the left hip and set 50 cm from the head during the night. Results showed exposure levels similar to other exposure surveys in Europe, such as the previous European project ARIMMORA and French EXPERS [20], [24], [26], [66], with the AM mean of 24h TWA equal to 0.13 µT and the GM 0.05 µT over all the participants. No conclusions were found about causality between MF exposure and non-specific physical symptoms.

The survey [22] aimed at assessing the prenatal exposure to ELF-MF and the possible impact on fetal growth. 24h measurements of 128 pregnant women at their 3^{dr} trimester were measured by EMDEX Lite meter in Minhang District, Shanghai. As in previous studies, the meter was worn at the waist level in daytime and placed next to bed during nighttime. Results were expressed in terms of TWA, median and 75th percentile for each of the 24h measurements, with values equal to 0.063 µT (0.63 mG) for TWA, to 0.038 µT (0.38 mG) for the median and 0.063 µT (0.63 mG) of the 75th percentile. Exposure to higher ELF-MF levels was hypothesized to be related with decreased fetal growth in girls, but not in boys. Authors concluded that a larger collection of measurements and subjects is necessary to confirm these findings.

C. Computational Modeling and Dose Assessment

Many studies based on the use of computational methods were focused on the assessment of the exposure levels due to ELF-MF due to transmission power lines. Different approaches were used with different goals: in [68], [69] computational methods were used to assess the ELF-MF generated in the vicinity of high voltage overhead power transmission. In [68] the authors compared ELF-MF emitted from basic types of overhead power lines for the most common types of towers in Czech and Slovak republic. For double-circuit lines, all possible phase conductor configurations were investigated. Comparison was made for 110 kV lines with ground clearance of 6 m and for 400 kV lines with ground clearance of 8 m and 12 m, showing that in all investigated cases, the levels of exposure were below the maximum limit defined by ICNIRP [29]. In [69] a similar approach was applied to assess the amplitude of the ELF-MF generated in the vicinity of high voltage overhead power transmission lines of the Algerian national transmission grid. Influence of loading current on the ELF-MF, as well as the variation of tower configuration and conductor section were investigated. All the ELF-MF values obtained in areas open to the public were below the ICNIRP safety exposure limit of 200 µT [29].

A high number of studies focused on the assessment of exposure due to transmission power lines by modeling in terms of amplitude of the EF induced in human tissues, by modeling the incoming MF as uniform. In [70] the compliance of exposure levels of pregnant women exposed to uniform MF at 50 Hz (with amplitude equal to 16, and 100 mT) to the Recommendation 1999/529/EU and the Directive 2013/35/EU was assessed by computational methods and highly detailed anatomical models. Results showed that, (i) EF in pregnant women were in compliance with the Directive, with exposure variations due to fetal posture of $<10\%$, (ii) EF in fetuses are lower than the occupational limits, with exposure variations due to fetal posture of $>40\%$ in head tissues, (iii) EF in fetal CNS tissues of head are above the ICNIRP 2010 guidelines [29] at 1 mT (in 7 and 9 months gestational age) and at 6 mT (in all gestational ages). In [71] the levels of exposure of pregnant women at 3, 7, 9 months gestational age to harmonic content of a uniform magnetic field at 50 Hz were assessed. Results showed that, although harmonic components added some contributions to the overall level of the EF induced in fetal tissues, these values were far lower than those ones induced by the main frequency at 50 Hz. The maximum E^{99} induced in fetus tissues, for all frequencies and across all the gestational ages was found to be equal to 16.7 μV/m/μT, well below ICNIRP guidelines [29]. To cope with main sources of uncertainty, i.e., the orientation of the MF and the variability of the estimation of the dielectric properties, four studies based on the use of stochastic dosimetry were reported. In [72], [73], [74], [75] the influence of the orientation of a uniform 50 Hz MF on the exposure levels for pregnant women [72] and children of various ages [73], [74] was assessed by stochastic dosimetry based on different uncertainty quantification methods. In all these studies results showed that the orientation of the MF was highly influential on the values of the EF induced in human tissues, but all the obtained values were well below the ICNIRP basic restrictions [29]. In [75] stochastic dosimetry was applied to the assessment of the influence of the uncertainty about the fetal tissues dielectric properties on the amplitude of the EF induced in fetal tissues when pregnant women were exposed to uniform 50 Hz MF with amplitude of 200 µT. Results suggested that, despite the considerable range of variability in the conductivity values, the influence on the compliance with the exposure guidelines were negligible.

A more recent study [76] focused on pre-birth exposure, investigating the amplitude of the EF induced in twin fetuses exposed to 50 Hz uniform MF. Results showed slightly higher EF amplitudes for twin tissues than for a single fetus, with a great dependence on the angle of incidence of the MF. The E^{99} was in the range 9.6%–34.8% for frontal incidence, 15.8%–34.8% for lateral incidence, and 14.2%–21.1% for top incidence, of the ICNIRP basic restrictions [29].

Another study [77] assessed infant exposure to 50 Hz MF from power lines by investigating variability due to posture and skin-to-skin contact. The $E^{99}{}_{\mathrm{CNS}}$ and $E^{99}{}_{\mathrm{PNS}}$ were used as metrics. The single (free of contact with others) infant model showed lower EF values compared with single adult and child models when exposed to the same 50 Hz MF, and that different postures of sitting, standing, or arm-up were not so influential. However, skin-to-skin contact with other models could significantly raise induced EF strength in the infant (e.g., contact on 0.93% of the infant's total surface increased $E^{99}{}_{\mathrm{PNS}}$ values by 213%).

Also in [78] the authors investigated EF induced in a realistic child model due to low-frequency contact current. The exposure levels observed in the child model were higher than those found for the adult, but always well below the corresponding ICNIRP basic restrictions [29]. To correlate EF induced by exposure to ELF-MF in laboratory mice and rats during in vivo experiments to those induced in children, in [79], four different approaches of mapping relative induced EF in tissue per T between humans and rodents have been proposed. Median induced EF in children younger than 10 years old were in the range 5.9–8.5 V/m per T. Maximum induced EF, generally in the skin, were between 48 V/m and 228 V/m per T. To achieve induced EF of comparable magnitude in rodents, external MF must be increased by a factor of 4.0 for rats and 7.4 for mice, while to achieve comparable MF dose, ratio is close to one.

The effect of the variability of the anatomical characteristics among individuals on the EF induced in brain tissues was assessed in a recent study [80]: the variation of the maximum EF strengths induced in the brain of 118 individuals when exposed to uniform magnetic fields at 50 Hz showed that individual characteristics, such as age and skull volume, as well as the incident MF direction, have a systematic effect on the peak EF values. Older individuals showed higher induced EF strengths, possibly due to age-related anatomical changes in brain, while higher peak EF were found for larger skull volumes.

Some studies focused on the assessment of the exposure due sources placed in proximity of the subjects, in near field conditions. In [81] human exposure to household induction cooktop was assessed by (i) measuring the emitted MF (ii) using numerical simulations involving equivalent sources of the induction cooktop and 3-D human models. Findings showed that exposure levels were lower than 1.27% of the ICNIRP 2010 basic restrictions [29].

In [82] stochastic dosimetry was used to assess children exposure variability due to low frequency near-field sources such as hairdryers model. Results showed that maximum values of EF amplitude were localized in the central nervous system, in the biggest tissues placed in the superficial part of the brain, namely, in brain grey and white matter. Moreover, a high exposure variability depending on the near-field source position was highlighted.

Among the near field ELF-EMF sources, also telecommunication technologies, such as mobile phones and cordless phones, usually investigated as radio-frequency EMF sources, were investigated in the framework of MOBI-Kids International project [83], [84]. In these studies the authors describe measurements and computational modelling to assess the ELF exposure of the brain from use of four different communication systems: Global System for Mobile (GSM), Universal Mobile Telecommunications System (UMTS), Digital Enhanced Cordless Telecommunications (DECT) and Wi-Fi Voice over Internet Protocol (VoIP).

The ELF-MF produced by the phones during transmission were measured under controlled laboratory conditions, and an equivalent loop was fitted to the data to produce three-dimensional extrapolations of the field. Computational modelling was then used to calculate the induced current density and EF strength in the brain of children of different ages and adults. Results indicate that the current densities induced in the brain during DECT calls are likely to be an order of magnitude lower than those generated during GSM calls but over twice that during UMTS calls. The average current density during Wi-Fi VoIP calls was found to be lower than for UMTS by 30%, but the variability across the samples investigated was high. Spectral contributions were important to consider in relation to current density, particularly for DECT phones. Results suggested that the spatial distribution of the ELF induced current densities in brain tissues is determined by the physical characteristics and position of the phone (battery position), while the amplitude is mainly dependent on communication system.

V. Discussion

The assessment of the human exposure levels in daily life scenarios to ELF-EMF sources, although being object of studies in the last 40 years, is still an on-going process. The aim of this review is thus to collect the newest literature studies about human ELF-EMF exposure of the years from 2015 to 2022 in different type of environments and with various type of measurements techniques. As a general remark, due to the different approaches used in assessing ELF-EMF exposure, the use of different recruitment strategies, as well as different averaging times reported in different publications, make findings described in different studies difficult to compare.

TABLE III
Summary of LF-EMF Exposure Levels

		Exposure levels
	Outdoor	
Spot and Long-Term Measurements	Sources: power lines	Min mean value – Max mean value 0.16 [35] – 3.5 μT [56] 3.9 – 769.4 V/m [57]
	Sources: transformer stations	Min mean value – Max mean value 0.02 – 7.03 μT [25]
	All outdoor sources	Min mean value – Max mean value 0.015 [59] – 0.14 μT [41]
	Indoor	
	School	Min mean value – Max mean value 0.015 μT [59] – 0.21 μT [40]
	Residential dwellings	Min mean value – Max mean value 0.019 [59] – 0.258 μT [63] 1.1 – 66.9 V/m [36]
	ELF Domestic Appliances	Min peak value – Max peak value 7.3 (Printer) – 472.5 μT (Appliance transformer) [39]
	IF Domestic Appliances	Min peak value – Max peak value 41.5 V/m (induction cookers) [11] – 471 V/m (fluorescent lamps)[65]
	Transport	
	Public Transport	Min mean value – Max mean value 0.03 – 2.6 μT [5]
	Electric Vehicles	Min mean value – Max mean value 0.04 –1.7 μT [5]
	Subjects	
Personal Exposure Measurements	Children/ Adolescents	Min GM – Max GM over 24h: 0.02 [20] – 0.29 μT [21]
	Pregnant Women	GM over 24h 0.038 μT [22]
	Adults	Min GM – Max GM over 24h 0.03 [24] –0.05 μT [23]
	Source	
Computational and Stochastic Methods	Power Lines	Min peak value – Max peak value 52.17 [68] – 1290.28 μT [69]
	Uniform Magnetic Fields	Min E^{99} – Max E^{99} in CNS 2.8 [73] –43.6 mV/m [80] Min E^{99} – Max E^{99} in PNS 5.2– 45 mV/m [76]

Table III shows a summary of the ELF-EMF exposure levels, in terms of minimum and maximum range of different quantities (i.e., mean, GM, peaks, E^{99} values in CNS and PNS), divided by the type of measurements strategies (i.e., Spot and Long-Term Measurements, Personal Exposure Measurements and Computational and Stochastic Methods). The quantities reported are based on the different type of literature studies, and in square brackets are indicated the references where the quantities could be found.

Considering only studies more recent than those described in the last survey about the ELF-EMF exposure [9], the majority of the research efforts based on long-term and spot measurements and focusing on the assessment of the exposure arising from outdoor power lines exposure levels where carried out in developing countries, in which the deployment/modernization of power line systems required the assessment of the levels of exposure (see, e.g., [35], [56]), while studies carried out in Europe were more focused on the measurement of the levels in microenvironments in which children spend most of their time, such as schools, outdoor parks and residential dwellings. When this latter, great importance was given to the presence of domestic appliances, at ELF range as well as IF range, due to their increasing presence and their proximity to the human body [11]. The highest long term and spot ELF-MF exposure levels were observed in near proximity to the power lines and transformer stations, with a maximum mean value obtained for the transformer equal to 7.03 μT [25]. Apart from this value, most measurements of background exposure levels in indoor and outdoor scenarios are similarly low, with a variation in the mean exposure levels between 0.15 μT – 0.26 μT, depending on the area and levels of urbanizations under investigation [59], [63]. In indoor environments, exposure was most due to domestic appliances and devices, both ELF and IF ranges. The highest peak exposure values were observed in proximity of the devices, with highest values for appliances transformer (472.5 μT) at ELF range and fluorescent lamps at IF range (471 V/m).

A particular attention was paid to means of transport: due to the great increasing of the use of fully electric and hybrid vehicles, a great effort towards the impact of these new sources on the everyday levels of exposure for general public will be deserved in the next years. ELF MF exposure levels in the context of transport systems were found to have maximum mean values equal to 2.6 μT in public transports and 1.7 μT in private electric vehicles [5].

As to the personal measurements, most of the studies were focused on early stage of life, from fetuses to adolescents. ELF-MF measurements showed almost no differences related to the subjects age, with 24 h GM values around 0.02 µT–0.05 µT [20], [22], [23], [24]. The only exception is the study of Valic et al. [21], where the 24h GM of children showed higher value around 0.29 µT. This can be explained by the ratio of participants living close to the source of ELF-EMF (e.g., power lines), higher than in the other studies.

Most computational studies were focused on the assessment of 99th percentile of induced EF in CNS and PNS in different child and fetus models when exposed to uniform magnetic fields at 50 Hz. Across all the studies, the maximum reported E^{99} peak value was found to be equal to 43.6 mV/m for CNS [80] and 45 mV/m for PNS [76]. Only few computational studies dealt with near field sources, making difficult to generalize the results reported by the different studies. In this context, stochastic and machine methods could offer feasible strategies in accounting for the variability and heterogeneity caused by near field sources.

VI. Conclusion

The observed ranges of exposure levels to ELF-EMF were coherent with the values observed in [9] about the exposure levels of general public in European countries, and all the measured levels of exposure were below the ICNIRP guidelines for general public exposure [29]. Furthermore, even if the validity of the attention level of long-term time-average exposures of 0.3–0.4 µT is still deeply debated, the studies collected about personal exposure measurements showed always GM values lower than 0.4 µT. As observed in [9], higher MF exposure levels have been measured in apartments closed to built-in power transformers, and the major part of exposure to ELF and IF EMF originates from electric devices, but the duration of such exposure is extremely limited.

In [16] the authors classified the exposure of European population to ELF-EMFs in three main classes, i.e., (i) intermittent variable partial body exposure; (ii) continuous elevated level whole body (WB) exposure and (iii) continuous low level background exposure.

This classification can be assumed to be still valid considering the findings of the studies analyzed in this work. Even with the advent of new technologies, it is still possible to classify the exposure scenarios in non-spatially uniform ELF-MF, due to sources relatively close to the exposed subject, and spatially uniform ELF-MF with high or low amplitude, depending on the distance from the sources. This type of classification, combined with the information arising from new studies focusing on ELF-EMF biological effects [85] will be useful for achieving an effective and reliable estimation of the potential health impact of exposure to ELF-EMF in incoming exposure scenarios. Future studies should be even more focused on assessing ELF-EMF exposure due to the new emerging technologies, such as electric transportation and new energy distribution systems.

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