Industrial Health 2022, **60**, 201–215

Review Article

Occupational exposure to radiofrequency electromagnetic fields

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Received June 9, 2021 and accepted October 8, 2021
Published online in J-STAGE November 16, 2021
DOI https://doi.org/10.2486/indhealth.2021-0129

Abstract: High exposures to radiofrequency electromagnetic fields (RF EMF) are possible in workplaces involving sources used for broadcasting, telecommunication, security and identification, remote sensing and the heating and drying of goods. A systematic literature review of occupational RF EMF exposure measurements could help to clarify where more attention to occupational safety may be needed. This review identifies specific sources of occupational RF EMF exposure and compares the published maximum exposures to occupational exposure limits. A systematic search for peer-reviewed publications was conducted via PubMed and Scopus. Relevant grey literature was collected via web searches. For each publication, the highest measured electric field strength, magnetic flux density or power density was extracted. Maximum exposures exceeding the limits were reported for dielectric heating, scanners for security and radiofrequency identification, plasma devices and broadcasting and telecommunication transmitters. Occupational exposure exceeding the limits was rare for microwave heating and radar applications. Some publications concerned cases studies of occupational accidents followed by a medical investigation of thermal health effects. These were found for broadcasting antennas, radar installations and a microwave oven and often involved maintenance personnel. New sources of occupational exposure such as those in fifth generation telecommunication systems or energy transition will require further assessment.

Key words: Electromagnetic fields, Radiofrequency, Exposure, Occupational, Regulation

Introduction

Radiofrequency electric, magnetic and electromagnetic fields (RF EMF) with frequencies from 100 kHz to 300 GHz can be used to convey information (broadcasting, telecommunication, radiofrequency identification), for remote sensing (radar, security scans) for heating and drying of goods and for medical diagnostic or therapeutic purposes. If they are sufficiently strong, RF EMF can lead to excessive heating and tissue damage. Some of the strongest human-made sources of EMF can be found in the workplace. The International Commission for Non-Ionizing Radiation Protection (ICNIRP) has defined basic restrictions in terms of the specific absorption rate (SAR) and power density in the body, below which these health effects will not occur[1, 2]. Reference levels in terms of the electric field strength, magnetic field strength or flux density and power density of the external fields outside the body have been derived from these basic restrictions. When workers are exposed to RF EMF weaker than the reference levels, the basic restrictions will not be exceeded under most circumstances, except for exposure of the limbs at frequencies between 100 kHz and

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Table 1. Exposure limit values for thermal effects in Directive 2013/35/EU

Frequency	Health effects ELV SAR (W/kg)	Health effects ELV power density (W/m^2)
100 kHz ≤ f < 6 GHz		
whole body average	0.4	–
localised 10 g, head and trunk	10	–
localised 10 g, limbs	20	–
6 GHz ≤ f < 300 GHz	–	50

Abbreviations: ELV, exposure limit value; SAR, specific absorption rate.
Note 1: Averaging mass for maximum localised SAR is any 10 g of contiguous tissue with roughly homogeneous electrical properties. Note 2: Power density shall be averaged over any 20 cm^2 of exposed area. Spatial maximum power densities averaged over 1 cm^2 should not exceed 20 times the value of 50 W/m^2. Power densities from 6 to 10 GHz are to be averaged over any six-minute period. Above 10 GHz, the power density shall be averaged over any $68/f^{1,05}$ -minute period (where f is the frequency in GHz).

110 MHz. For this frequency range, separate reference levels were set for limb current, since exposure below the action levels for electric field strength does not guarantee that the SAR in the limbs, with their relatively small diameter, is not exceeded. The European Union (EU) has used the 1998 ICNIRP basic restrictions and reference levels to set legal limits for worker exposure to RF EMF in its occupational health and safety legislation by way of Directive 2013/35/EU (further called ‘EU Directive’). In the EU Directive, the reference levels are called ‘action levels’ and the basic restrictions ‘exposure limit values’ (Table 1 and Table 2)[3]. Although the original transposition deadline was 1 July 2016, due to delays in the legal process in some member states the EU directive had been implemented in all EU member states by August 2017[4].

A systematic assessment of published studies on occupational RF EMF exposure could help to clarify where more attention to occupational safety may be needed. The European Commission has published a guide of good practice for the EU Directive, which tabulates working environments in which the action levels may be exceeded and further risk assessment is required[5]. On the basis of the good practice guide and the results of a search with general RF EMF search terms (see ‘methods’ section), six categories of working environments were selected for review of occupational RF EMF exposure.

In the category of dielectric heating, a dielectric material (polarisable insulator) is placed in an alternating RF EMF between two electrodes, resulting in energy absorption without conduction and consequently heating. It is mainly used to deform, melt, weld or seal plastic materials[6]. Frequencies for this application lie between 4 and 70 MHz, with a strong concentration in the 27 MHz band. The same physical principle is employed at higher frequencies (mainly at 915 MHz and 2.45 GHz) for microwave heating of food, wood and ceramics for purposes of drying, curing, shaping, sterilisation or pest control[7]. In the category security and radiofrequency identification (RFID), RF EMF in the frequency bands around 100 kHz, 10 MHz, 1 GHz and 24 GHz are used for article detection and identification and for security scans of persons and objects[8]. In industrial processes involving plasma etching, plasma sputtering and vapour deposition, RF EMF are used to apply thin layers of material to components in the electronics industry[9]. In the category broadcasting and telecommunication, RF EMF are employed to convey radio and television signals and information for mobile communication and wireless data transfer by the general public and by industry, air and marine traffic control, the emergency services and the military. Frequency use ranges widely between 100 kHz and 300 GHz[10]. Radar uses the reflection of RF EMF to determine the range, angle, velocity or composition of objects. It can be applied to detect and analyse the motion or composition of aircraft, missiles, ships, vehicles, weather formations, terrain and soil layers. Frequency bands vary according to application from 3 MHz to 110 GHz[11].

The present review complements two earlier reviews using the same methodology. The most recent of these (2018) focused on low frequency and RF EMF sources that are exclusively used in medical, physiotherapy or dental practice[12]. These sources of occupational exposure have therefore been excluded from the present review. Occupational

Table 2. Action levels for thermal effects in Directive 2013/35/EU

Frequency	AL electric field strength (V/m)	AL magnetic flux density (µT)	AL power density (W/m^2)
100 kHz $\le f <$ 1 MHz	6.1×10^{2}	$2.0\times10^{6}/f$	–
$1 \le f <$ 10 MHz	$6.1\times10^{2}/f$	$2.0\times10^{6}/f$	–
$10 \le f <$ 400 MHz	61	0.2	–
400 MHz $\le f <$ 2 GHz	$3\times10^{-3}\sqrt{f}$	$1.0\times10^{-5}\sqrt{f}$	–
$2 \le f <$ 6 GHz	1.4×10^{2}	4.5×10^{-1}	–
$6 \le f <$ 300 GHz	1.4×10^{2}	4.5×10^{-1}	50

Abbreviations: AL, action level.

Note 1: f is the frequency in hertz (Hz). Note 2: Squared AL for electric field strength or magnetic flux density are to be averaged over a six-minute period. For RF pulses, the peak power density averaged over the pulse width shall not exceed 1,000 times the respective AL value. For multi-frequency fields, the analysis shall be based on summation, as explained in the practical guides referred to in Article 14 of the EU Directive. Note 3: AL for electric field strength or magnetic flux density represent maximum calculated or measured values at the workers' body position. In specific non-uniform conditions, criteria for the spatial averaging of measured fields based on established dosimetry will be laid down in the practical guides referred to in Article 14 of the EU Directive. In the case of a very localised source within a distance of a few centimetres from the body, compliance with ELVs shall be determined dosimetrically, case by case. Note 4: Power density shall be averaged over any 20 cm^2 of exposed area. Spatial maximum power densities averaged over 1 cm^2 should not exceed 20 times the value of 50 W/m^2. Power densities from 6 to 10 GHz are to be averaged over any six-minute period. Above 10 GHz, the power density shall be averaged over any $68/f^{1.05}$ -minute period (where f is the frequency in GHz).

exposure to low frequency magnetic fields was reviewed in 2014[13)], which included induction heaters with frequencies up to 1 MHz. Sources that are also used by the general population outside the workplace, such as mobile phones and other wireless consumer products, also fall outside the scope of the present review.

Methods

Data collection

A systematic literature search for peer-reviewed articles on occupational exposure to RF EMF published up to December 2020 was conducted in PubMed (http://www.ncbi.nlm.nih.gov/pubmed/) and Scopus (http://www.scopus.com/). Pagination of advance publications was added if available before submission of the manuscript. For a first general search, a combination of blocks of search terms were used, relating to RF EMF [((“radio frequ*” OR radiofrequ* OR rf OR microwave* OR “millimeter wave*” OR “millimetre wave*” OR “mm wave*” OR radar*) AND (field* OR radiat* OR wave*))], occupational setting [(worker* OR occupation* OR workplace OR employ* OR working OR “work floor”)] and exposure [(exposure OR dosimetry OR intensity OR “power densit*” OR “field strength*” OR “flux densit*” OR “specific absorption” OR sar)] but excluding frequencies in the range of optical radiation [(NOT (“optical radiation” OR ultraviolet OR uv OR infrared OR “visible light”)]. Secondly, searches for specific sources of occupational exposure to RF EMF were conducted in Pubmed and Scopus, using a combination of the search terms related to RF EMF and occupational setting (see above) with each of the following sets of source-specific search terms: [((dielectric* OR plastic) AND (heating OR heater* OR welding OR welder* OR sealing OR sealer* OR curing OR curer*))]; [(oven* OR drying OR dryer*)]; [(“article surveill*” OR antitheft* OR “anti theft*” OR security* OR rfid* OR “radiofrequency identification*”)]; [(telecom* OR radio OR television OR broadcast* OR tetra OR c2000) AND (mast* OR antenna* OR transmitter* OR station* OR beacon* OR tower*)]; [(radar*)]; [(military OR “armed forces” OR aircrew* OR soldier* OR sailor* OR army OR airforce* OR “air force*” OR navy)]; [(wireless AND “power transfer*”)]; [(plasma AND (etching OR sputtering OR stripping OR “vacuum deposition*” OR “surface treatment*”)]. In Scopus, document types such as conference abstracts that were not full journal articles were excluded, as well as subject categories not relevant for RF EMF exposure (SUBJAREA, “MATE”;

SUBBJAREA, “CHEM”; SUBJAREA, “CENG”; SUBJAREA, “EART”; SUBJAREA, “BUSI”; SUBJAREA, “ARTS”; SUBJAREA, “ECON”). For Pubmed, 1,879 results were found with the general search terms and 2,397 with the source-specific search terms (with an unknown overlap between the two). After screening of titles and, if necessary for clarification, abstracts, 89 articles were selected as potentially relevant, 31 of which were discarded after full-text screening for lack of suitable individual exposure values. For Scopus, 1,771 results were found with the general search terms and 3,662 with the source-specific search terms (with an unknown overlap between the two). After screening of titles and, if necessary for clarification, abstracts, 42 articles were selected as potentially relevant and were not also found with the Pubmed search, 27 of which were discarded after full-text screening for lack of suitable individual exposure values.

Relevant grey literature (measurement reports) in English, German, French or Dutch was identified on the websites of the following organisations: Agence nationale de securité sanitaire, alimentation, environnement, travail (ANSES) (France), Bundesamt für Strahlenschutz (Germany), Deutsche Gesetzliche Unfallversicherung (Germany), European Commission (Brussels), Health and Safety Executive (UK), Institut national de recherche et de sécurité (INRS) (France), Istituto Nazionale per l’Assicurazione contro gli Infortuni sul Lavoro (INAIL) (Italy), National Institute for Occupational Safety and Health (NIOSH) (USA), National Technical Reports Library (USA), Public Health England (UK), TNO (Netherlands), Vito (Belgium).

Data extraction

Only those publications listing individual maximum exposure values at specific frequencies were used, because frequency-averaged or group-averaged data make it impossible to compare maximum individual exposures to the action levels (reference levels) or exposure limit values (basic restrictions). Where the exposure was listed as a proportion of the action levels, the actual exposure was calculated by multiplying with the action level at the relevant frequency. Wherever possible, for frequencies below 10 GHz the 6-minute averaged values were used in accordance with the EU Directive and the underlying 1998 ICNIRP guidelines. Where only measurements in shorter time intervals were available, this is clearly mentioned as a caveat when comparing with the exposure limits. Where exposure was intermittent and the duty cycle was given, exposure values corrected for duty cycle were used. Where multiple publications were produced by the same authors, based on same subjects and study protocol, the maximum exposure values were extracted from only one of these publications. Apart from the distance to the source, worker exposure from radiofrequency devices also depends on the output power of the device in question (for example for dielectric heating equipment). It was assumed that the maximum exposures extracted are associated with the highest output power under normal working conditions. Where available, both maximum electric field and magnetic field measurement values were extracted for the same exposure since these may not always be coupled at the place of exposure. In accordance with the EU Directive, all magnetic field measurements are presented as magnetic flux density. Where only the magnetic field strength was available, the magnetic flux density was calculated by multiplying with the magnetic permeability ($4\pi \times 10^{-7}$ H/m). For radar exposure, where the (equivalent) frequency exceeded 6 GHz for a substantial proportion of measurements and energy deposition is limited to the outer layer of the body, the maximum equivalent plain wave power density was extracted for comparison with the exposure limits. In the minority of radar publications where only electric field strength was given at such frequencies, the power density was calculated using the formula: $S = E^2/Z$ with $Z = 377\ \Omega$. For lower frequencies and the minority of publications where only the maximum power density was given, this was converted to electric field strength for easier comparison, using the formula: $E = \sqrt{(S \times Z)}$ with $Z = 377\ \Omega$. For pulsed fields, such as those of some radar devices, the peak power density in the pulse was extracted where available and compared with the relevant action level (reference level) times 1,000 (for power density), as instructed in the EU Directive and underlying ICNIRP guidelines. Where peak values were measured or calculated, they have been converted to root-mean-square (rms) values by dividing by $\sqrt{2}$, for comparison with the action levels. Where no mention of peak or rms values was made in the publication, rms values were assumed. Exposure measurements were directly compared to action levels, without taking measurement uncertainty into account, since the source publication did not generally provide sufficient information on measurement uncertainty.

Exposure at the main frequency component with highest exposure was used, even though higher harmonics may also contribute to exposure. Where action levels are exceeded, this should be seen as an indication that there are potential issues with exposure levels for higher harmonics and that the frequency-summated exposure may be higher. The highest value of electric field strength, magnetic flux density or power density measured at the actual workplace

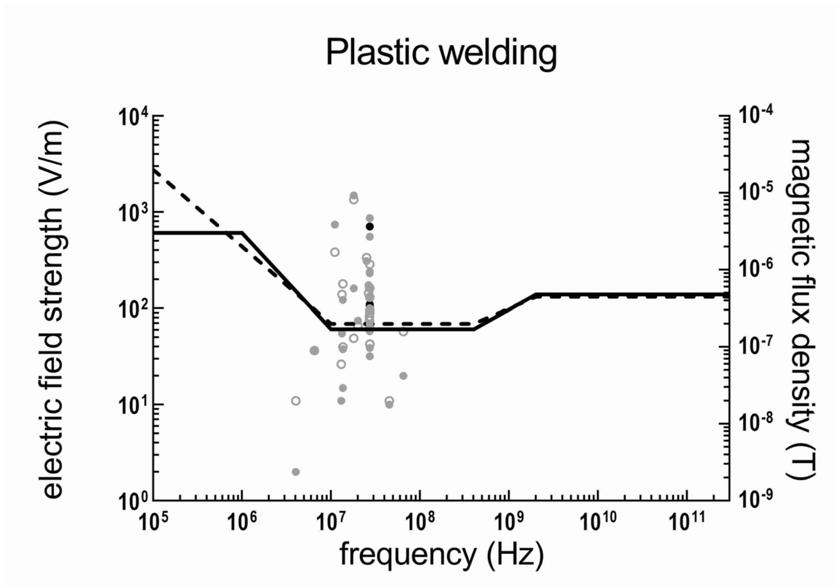

Fig. 1. Maximum electric field strength (left y-axis) and magnetic flux density (right y-axis) at the worker's position per publication, per main frequency component for dielectric heating of plastic.
Legend: — = electric field action levels; --- = magnetic field action levels; ● = electric field strength; ○ = magnetic flux density. Symbols in grey represent data published before 2012 and symbols in black data published in or after 2012. Literature references used: [14–36].

was used as an indicator of maximum exposure to the source. When this was not available (usually when fields were measured at standardised distances to the source), the highest value measured at a distance that was possible with intended or foreseeable use was taken. When measurements were made at multiple heights from the floor, the height with the highest exposure was chosen. Not all publications contained sufficient information to determine whether the maximum measured values listed were restricted to the limbs. Where insufficient information was available it was presumed that all measured values may have involved head or trunk exposure. In the figures, a distinction is made between data points from publications before 2012 and data published from 2012 onwards, since it had become clear by then that the 2013 EU Directive would be applying legally binding exposure limits based on the 1998 ICNIRP guidelines.

For those publications in which the SAR or absorbed power density were calculated, these data are discussed in the text and related to the relevant exposure limit value (basic restriction). In some publications exposure was clearly due to an accident, where possible exposure above the limit values was suspected and an occupational medical investigation was conducted. Data from these publications are not included in the figures, but discussed separately in the text for each category of working environment.

Results

Dielectric heating (plastic welding)

A total of 25 publications had data on worker exposure near devices for dielectric heating to deform, melt, weld or seal plastic materials (3 of which published after 2011). Most of these investigations corrected for the fact that the apparatus was only active for part of the 6-minute averaging period ('duty cycle' smaller than 1), making the time-averaged exposure lower than that in the active period. The highest measured electric field strengths and magnetic flux densities to which workers could be exposed are shown in Fig. 1. The majority of these highest exposure values were above the action levels in the EU Directive for the electric as well as the magnetic field. In 2 publications with transgression of action levels the local and whole body averaged SAR was calculated[26, 31]. In one of these, the situation with transgression of the action levels also resulted in a local SAR in the legs that exceeded the exposure limit value[26]. In 3 out of the 7 publications where the limb current was measured, this could exceed the action level[27, 29, 35]. In working environments where action levels are exceeded, EU Directive requires that the employer takes mea-

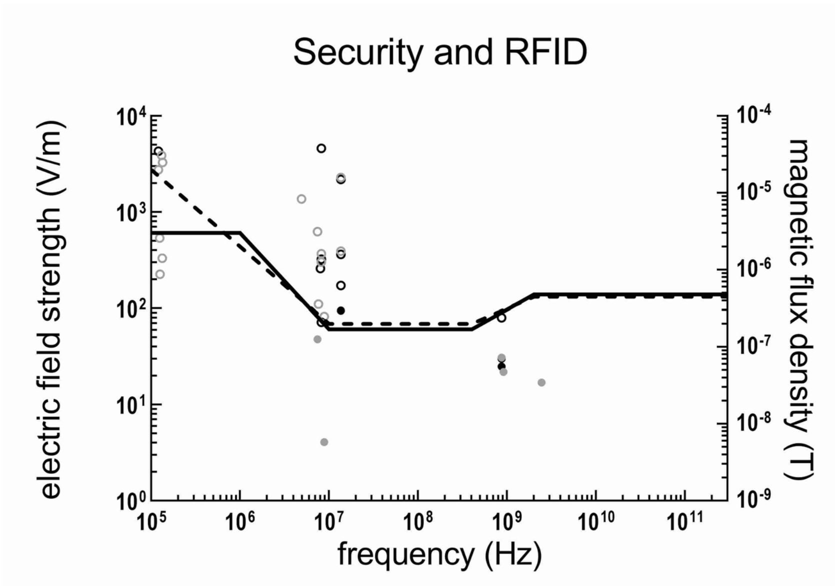

Fig. 2. Maximum electric field strength (left y-axis) and magnetic flux density (right y-axis) at the worker's position per publication, per main frequency component for security gates and scanners and RFID scanners or active transponders.
Legend: — = electric field action levels; --- = magnetic field action levels; ● = electric field strength; ○ = magnetic flux density. Symbols in grey represent data published before 2012 and symbols in black data published in or after 2012. Literature references used: [33, 37–52]

sures to reduce exposure, or demonstrates that the exposure limit values are not exceeded. Some publications investigated the effect of exposure reduction measures and showed that the field strength remained below the action levels after applying appropriate shielding to the device[16, 25, 36].

Security and RFID

A total of 17 publications had data on worker exposure near devices for security scans or RFID (6 of which published after 2011). These concerned measurements of (potential) workplaces near gates or hand-held scanners for the detection or deactivation of anti-theft labels in shops, security scanners in public buildings including airports and scanners for the identification of objects via RFID (e.g., access passes, goods). The highest measured field strengths and magnetic flux densities to which workers could be exposed are shown in Fig. 2. For body scanners using millimetre waves (frequencies around 2.4 GHz) the field strength was always lower than the action levels and the calculated SAR was below the exposure limit values[45, 46]. For anti-theft gates and RFID-scanners, which use RF EMF with frequencies around 100 kHz and 10 MHz, the majority of maximum exposure values was higher than the action levels, both for publications before and after 2012. However, an important caveat is that the exposure was not averaged over 6 minutes in these publications and the realistic exposure duration was not investigated. In 6 publications the local and whole body averaged SAR were calulated[40, 45–48, 51]. One of these showed a whole body averaged SAR higher than the exposure limit value, if exposure lasted longer than 6 minutes[48]. Contact currents were reported in 1 publication, but these did not exceed the action level[40].

Plasma devices

A total of 3 publications had data on worker exposure near equipment for radiofrequency industrial surface treatments, including plasma etching, plasma sputtering and vacuum deposition (2 of which published after 2011) (Fig. 3). Action levels were exceeded near (closer than 10 cm to) a device for plasma sputtering operating at 13.6 MHz[40] and near a microwave generator used for plasma excitation operating at 2.3 GHz[54]. If exposure would last sufficiently shorter than 6 minutes or if a greater distance could be observed, exposure would be expected to remain under the action levels. In 1 publication contact currents were measured, which exceeded the action level with a device for plasma sputtering (both touch and grasp contact), but not with a device for plasma-etching[40].

Broadcasting and telecommunication

A total of 31 publications had data on worker exposure in working environments near broadcasting antennas (radio

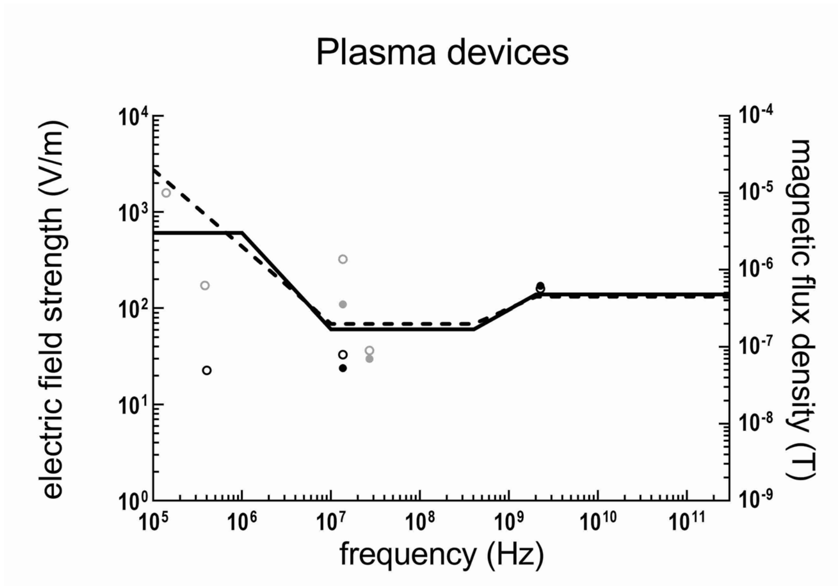

Fig. 3. Maximum electric field strength (left y-axis) and magnetic flux density (right y-axis) at the worker's position per publication, per main frequency component for plasma devices (plasma etching, plasma sputtering and vapour deposition).
Legend: — = electric field action levels; --- = magnetic field action levels; ● = electric field strength; ○ = magnetic flux density. Symbols in grey represent data published before 2012 and symbols in black data published in or after 2012. Literature references used: [40, 53, 54]

and television) or antennas or professional user devices for mobile telecommunication (telecom operators, company mobile radio, emergency services, armed forces), 14 of which were published after 2011. Maximum occupational exposure exceeding the action levels occurred more frequently for broadcasting antennas than for telecommunication antennas and in most cases was found in publications before 2012 (Fig. 4). The majority of publications assumed that exposure could last at least 6 minutes, but it was not usually reported how likely that was to happen in normal work activities. In 2 publications concerning workers near an FM antenna the SAR was calculated where the action levels were exceeded and was found to exceed the exposure limit value for the whole body[73, 81]. In 5 publications concerning networks for the emergency services, the local SAR exposure limit value for handsets or vehicle antennas was not exceeded[66, 67, 82–84]. The local head SAR was exceeded during maintenance work on an unscreened portaphone transmitter[58]. Limb current was measured and exceeded the action level in 1 publication for medium frequency (1.3 MHz) and high frequency (6 MHz) transmitters, but in both cases the action levels for electric field strength were also exceeded[63]. Contact currents were reported in 1 publication (military high frequency antenna), but these did not exceed the action level[64]. Three publications (not shown in graph) concerned an accident (incident where overexposure was suspected), followed by a medical examination. In the first of these, the exposure of maintenance personnel near a broadcasting antenna proved to be lower than the action levels[85]. In a second case study, a maintenance lift got stuck in front of a broadcasting antenna, where the exposure was 4 times the action level for 2.5 minutes. Registered symptoms were an acute feeling of warmth and skin redness, headache, diarrhoea, malaise and paresthesia which lasted several days after the incident[86]. A second publication by the same author reported similar symptoms in case studies of antenna engineers working near broadcasting antennas for extended periods, where action levels could have been exceeded[87].

Microwave drying and heating

A total of 5 publications had data on worker exposure near devices for drying, curing or heat sterilisation of goods (1 published after 2011). Four of these used microwave frequencies (2.5 GHz) and showed that the maximum power density at the workplace was lower than the action level (Fig. 5). One publication showed exposure higher than the action level for one of the two devices investigated, but this concerned an oven where the shielding door had a defect[88]. One publication concerned radiofrequency textile driers operating at 27 MHz, where electric field strength and magnetic flux density immediately next to the opening could

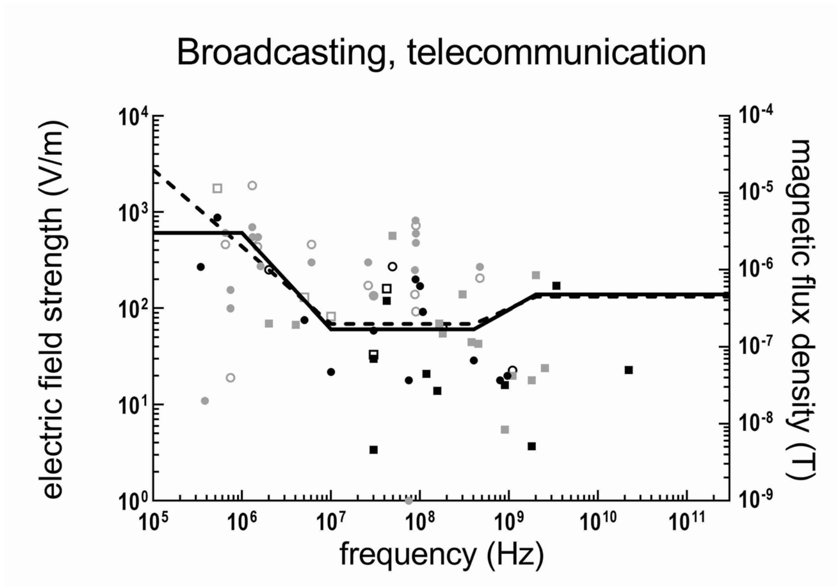

Fig. 4. Maximum electric field strength (left y-axis) and magnetic flux density (right y-axis) at the worker's position per publication, per main frequency component for broadcasting and telecommunication antennas.
Legend: — = electric field action levels; --- = magnetic field action levels; ● = electric field strength, broadcasting; ○ = magnetic flux density, broadcasting; ■ = electric field strength, telecommunication; □ = magnetic flux density, telecommunication. Symbols in grey represent data published before 2012 and symbols in black data published in or after 2012. Literature references used: [27, 53, 55–81]

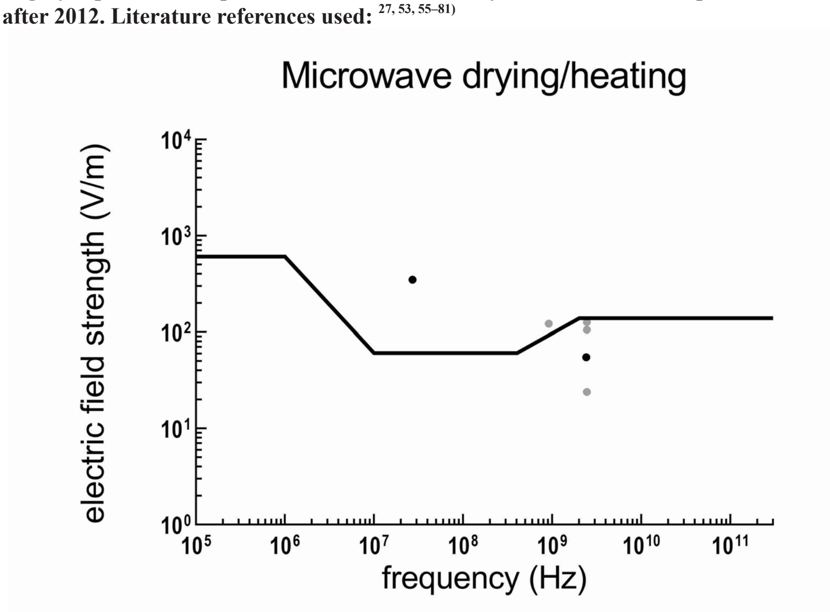

Fig. 5. Maximum electric field strength at the worker's position per publication, per main frequency component for industrial drying or heating processes.
Legend: — = electric field strength action levels; ● = electric field strength. Symbols in grey represent data published before 2012 and symbols in black data published in or after 2012. Literature references used: [40, 88–91]

exceed the action levels five-fold, presuming an exposure of at least 6 minutes[91]. One publication concerned an accident (incident where overexposure was suspected), followed by a medical examination. A maintenance worker repairing microwave ovens (2.5 GHz) with interrupted interlock protection was exposed to a power density of four times the action level, on repeated occasions with a duration of at least 4 minutes. Symptoms were a feeling of warmth, skin redness and a burning sensation in the eyes[92].

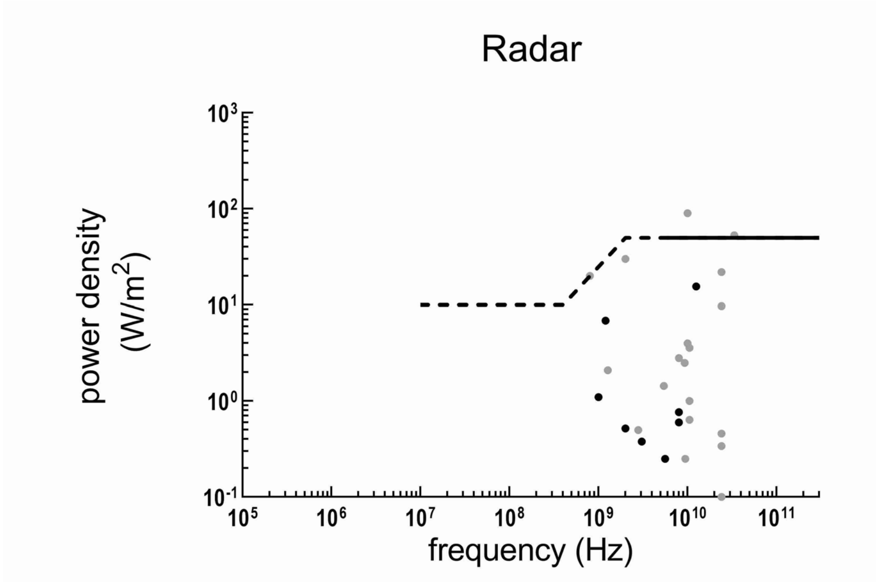

Fig. 6. Maximum equivalent plain wave power density at the worker's position per publication, per main frequency component for radar devices.
Legend: — = power density action levels; --- = ICNIRP 1998 power density reference levels; ● = power density. Symbols in grey represent data published before 2012 and symbols in black data published in or after 2012. Literature references used: [27, 53, 57, 69, 71, 76, 80, 93–105]

Radar

A total of 20 publications had data on worker exposure in working environments involving radar installations for identification and analysis of aircraft, missiles, shipping, cloud formations or for road speed detection. Five of these were published after 2011 and 6 publications concerned military installations. When determining exposure, the fact was taken into account that for certain radar applications the bundle moves or rotates and exposure only occurs part of the time ('duty cycle'). In the majority of publications, exposure was lower than the power density action levels (Fig. 6). Exposure exceeding the action levels was reported in 2 publications. The first of these concerned a police officer located in the bundle of a speed detector, which may be considered as unintended use[100]. The second concerned the operator of a military target radar[101]. For pulsed radar, apart from the time-averaged exposure, the peak exposure in the pulses is important. The reference level for power density for peak exposure in the pulse is 1,000 times the reference level for time-averaged exposure[1, 3]. For the 3 publications in which the peak exposure in the pulse was given (air traffic and shipping radar), this was lower than 1,000 times the action level[53, 103, 104]. Five publications (not shown in graph) concerned an accident (incident where overexposure was suspected), followed by a medical examination. All of these involved military radar applications: 3 publications with exposure of maintenance personnel (1.5 to 3 times the action level)[106–108] and 2 publications with onboard exposure of navy personnel to RF EMF from a target location radar (4 times the action level)[109] or the area radar of a closely passing ship (10 times the action level)[110]. In the latter case, the action levels for peak exposure in the pulse and the exposure limit value for whole body SAR were also exceeded. Recorded symptoms varied from psychological stress to a feeling of warmth, malaise, pain, dizziness, nausea or irritated eyes.

Other sources

One publication was found which assessed occupational RF EMF in a scientific laboratory (nuclear facility). Electric field strength near a pump source for laser radiation (5 MHz) and near an RF quadrupole accelerator (55 MHz) were in the order of 1% of the action levels[111]. The publications that were found on the strength of RF EMF associated with wireless power transfer did not specifically concern occupational exposure.

Discussion

The results of this systematic literature review show that the action levels and exposure limit values for RF EMF in the EU Directive (derived from the 1998 ICNIRP guidelines) can be exceeded, in varying proportions, for maximum exposures in working environments involving dielectric heating of plastic materials, security or RFID scanners, plasma devices, broadcasting and telecommunication, but only rarely for microwave drying or heating and radar.

For plastic welding using RF EMF-induced dielectric heating, the majority of highest exposure values registered exceeded the action levels. Since these publications usually took account of time-averaging and duty cycle, the possibility of overexposure is realistic in these cases and exposure reduction measures would be in order. The alternative is to calculate whether the SAR basic restrictions are not exceeded, but this is normally unrealistic for employers since the necessary calculations and computer simulations can be generally only be performed by experts in numerical dosimetry[112)]. A similar potential for maximal exposures exceeding the action levels occurs with textile or glue dryers which operate in the same ('diathermy') frequency band of 27 MHz[91)]. The available literature seems to indicate that there is less potential for overexposure for microwave drying, curing or sterilisation, provided that shielding doors are in good working order. Exposure reduction for plastic welding or other industrial applications of diathermy can involve the application of shielding or replacement with new equipment with more effective shielding, the removal of reflecting objects near the workplace, effective grounding and proper maintenance[16, 25, 36)].

For security and RFID-scanners, the majority of publications reported instantaneous maximum exposure levels higher than the action levels. However, the 6-minute averaged exposure can still remain under the action levels if the exposure duration is short enough. One would expect that this would usually be the case, unless the worker lingers next to a security gate for longer periods of time. The simplest control measures here would be increasing the distance to the scanner and limiting the time near the scanner when close approach is deemed necessary. For full body scanners using millimetre waves, overexposure is not an issue, even if workers are scanned themselves for security reasons.

For radiofrequency plasma devices, it is possible that action levels are exceeded close to the source, but again this presupposes that the worker's exposure lasts 6 minutes or longer. Ineffective shielding (panelling or casing) may be a source of avoidable high exposure for plasma devices. In an extreme case, when maintenance is performed on an active device by a worker inside the protective panelling, the exposure close to the device can be 10 times the action level[53)]. This underlines the need to pay special attention to maintenance workers in risk assessments for occupational RF EMF exposure.

For broadcasting and telecommunication antennas, there was evidence that the maximum exposures could exceed the action levels and exposure limit values near the antenna installation, again assuming that they would last at least 6 minutes. Unlike publications before 2012, the majority of publications after 2011 gave maximum occupational exposures lower than the action levels, although higher exposures could still occur for both broadcasting and telecommunication antennas. This may indicate increasing awareness of the legal exposure limits, coupled to the technical know-how on monitoring worker exposure in the broadcasting and telecommunication sector. Local SAR from handsets specific for the working environment under normal use (company networks, emergency services, armed forces) did not exceed the exposure limit values. The only exposure exceeding the local SAR was found for maintenance work on an unscreened portaphone older than 1991, again underlining the potential for higher exposure of maintenance personnel[58)]. The three case studies on overexposure accidents at antenna sites associated with a medical examination also concerned personnel performing maintenance work[85–87)].

For radar, the vast majority of published maximum workplace exposures under normal working conditions was lower than the action levels. Of the three publications which found an exposure higher than the action levels, one concerned a mechanic at an aircraft manufacturer ('maintenance')[103)], one a military radar operator[101)] and one a policeman in the beam of a traffic scanner[100)], which could be considered unintended use. In the latter publication, only 0.4% of all workplace measurements performed exceeded the action levels. The five accidental overexposure incidents with medical examinations all concerned military radar systems. Three of them involved maintenance personnel[106–108)] and the two remaining case studies concerned navy personnel accidentally exposed to radar beams from target locators[109)] or from a closely passing ship[110)]. Only one publication was found on the varied RF EMF exposures that can occur in the setting of research laboratories. More attention to these potentially diverse working environments may be warranted.

As discussed in the preceding reviews[12, 13)], the approach to reviewing maximum exposures with regard to exposure limits has several limitations. Only the maximum exposures at the workplace per frequency per publication are listed as an indication of worst-case conditions. They were usually performed at a fixed height and did not take account of spatial averaging, giving a conservative estimate of exposure[5)]. These maximum exposures are not necessarily representative of the majority of exposures and may not always represent good working practice. For dielectric heating (e.g., plastic welding) in particular, most of the literature database is older than 2012, and it may be that more recent devices in combination with mitigation measures have reduced the potential for worker overexposure. On the other hand, it cannot be excluded that even higher exposures are possible in working environments or scenarios that are not covered by the publications reviewed here. A comparison with the limits in the EU Directive was only made for the main frequency of the source in question. Other frequency components may add to the total exposure and multiple RF EMF sources in the same workplace also need to be added to total exposure. When comparing exposure measurements to legal limits, measurement uncertainty needs to be taken into account[5)], but source publications in the present review did not generally provide sufficient information to assess the impact of measurement uncertainty.

The technology of sources of occupational RF EMF exposure continues to evolve. Exposure guidelines and regulation likewise need to evolve to incorporate these developments, as do the techniques used to assess occupational exposure. One example of such developments are the new applications that are becoming available in the fifth generation of mobile telecommunication systems (5G). The higher frequencies and more superficial energy deposition, the use of beam forming, the more widespread use of small cells and local networks for machine-to-machine communication and the use of ultra-wideband pulsed fields do not necessarily create higher exposures, but do make exposure assessments more complicated[113, 114)]. Apart from some limited adjustment of reference levels and averaging times, the most recent ICNIRP guidelines for RF EMF introduce new limits for brief, localised exposure at frequencies from 400 MHz to 300 GHz, which are relevant in this context[2)]. It should be investigated whether these limits for brief, localised exposures raise new compliance issues for the types of working environments discussed in this review. Another example of novel types of exposure is the increased use of wireless power transfer, for example in charging electric vehicles such as busses and trucks, which generally uses RF EMF in the frequency range from 100 kHz to 50 MHz[115)]. Publications in recent years indicate that nearby exposure is lower than the action levels, but these assessments were not specific for occupational exposure[116, 117)]. Further investigation of occupational exposure scenarios would be useful.

Acknowledgements

This study was supported by a project grant from the Ministry of Social Affairs and Employment, the Netherlands (Z/110071/20).

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