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Exposure to Optical Radiation and Electromagnetic Fields at the Workplace: Criteria for Occupational Health Surveillance According to Current European Legislation

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A B S T R A C T

A very large number of workers is occupationally exposed to Optical Radiation (OR) worldwide, while indeed nowadays an exposure to Electromagnetic fields (EMF) can occur in almost all workplaces. OR origin can be natural, including the most relevant source, i.e. the sun, or artificial, that can be further classified in incoherent and coherent, i.e. the LASERs. Solar radiation (SR) exposure, and in particular its most harmful component, the ultraviolet radiation (UVR), is a significant occupational risk in "outdoor workers", including e.g. farmers and construction workers. UVR is mainly absorbed in the eye and the skin, there inducing various short-term and chronic adverse health effects, as burns, cataract and skin cancers. At least in Europe, for SR exposed workers no specific obligations currently exist regarding the Health Surveillance (HS), that is instead required for occupational exposures to artificial OR according to the legislation of the European Union (EU, Directive 2006/25/EC). Considering now EMF, the EU Directive 2013/35/EU provides an obligation for the HS of exposed workers, aimed at the prevention of the possible direct short-term effects, as involuntary contractions or temperature increase of tissues, and indirect effects, as shocks and interference. Conversely, long-term effects are not considered in the Directive as data on causal relationship, including reliable mechanisms, are considered inadequate. Direct short-term and indirect effects can appear solely in case of high exposures, usually occuring only accidentally, but a specific group of workers, defined "at particular risk", exists, and it includes e.g. persons with implanted active medical devices, as cardioverter defibrillators or pacemakers. In these workers, adverse effects can be induced at lower EMF levels. The identification and an adequate protection of the workers at particular risk is one of the main goals of the HS of occupational EMF exposure.
The main HS criteria applicable for workers with exposure to OR and EMF are discussed in this article.

1. Introduction

Exposure to Optical Radiation (OR) and Electromagnetic Fields (EMF), i.e. Non-Ionizing Radiation (NIR), at work represents a relevant occupational risk for many work activities: this paper is an extension of work originally presented in the 2020 IEEE International Conference on Environment and Electrical Engineering and 2020 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe) [1].

Occupational risks can be classified in chemical, biological, physical risks and others (including ergonomic, psichosocial and safety risks) [2]. NIR exposure is included among physical risks together with e.g. noise and vibrations. As it happens for all the other occupational risks, adequate prevention should be emplaced in the companies in order to warrant appropriate occupational health and safety (OHS) conditions for the exposed workers. This involves a specific evaluation of the risk related to the working activity with NIR exposure, aimed at identifying the most appropriate preventive measures. An important part of the prevention process to ensure OHS is the health surveillance (HS) of the workers exposed to occupational risks that may affect their health, usually performed by trained occupational physicians. HS is defined, according to the International Labour Office (ILO), as a group of "procedures and investigations to assess workers' health,

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in order to identify any abnormality possibly associated to a recognized work-related risk in exposed workers", involving "the review of the health records and any other opportune medical examinations needed" [3]. Considering possible implications for workers' health of NIR exposure, it should be noted that NIR are included in the part of the elctromagnetic spectrum with lower energy compared to ionizing radiation, meaning that both OR and EMF have not enough energy to cause ionization, i.e. to remove electrons from atoms and molecules. Accordingly, the interaction mechanisms with the biological tissues, and the penetration ability of NIR are very different from ionizing radiation. Nevertheless, also within the various regions and sub-regions of the NIR spectrum significant differences exist, and therefore the possible health effects and the criteria for the health surveillance of the workers exposed to non-ionizing radiation should be discussed separately. In the following parts of this article these criteria are introduced and discussed.

2. Optical radiation: occupational exposure and health effects

2.1. Occupational exposure to optical radiation

OR includes wavelengths (λ) between 100 nanometers (nm) and 1 millimeter (mm), distributed in three different regions: ultraviolet radiation (UVR), further classified in the subregions UV-A, UV-B and UV-C, visible radiation and infrared radiation (IR), with other three sub-regions: IR-A, IR-B and IR-C [4].

Occupational OR exposure can be possible both in case of artificial OR and solar radiation (SR) exposure.

Artificial sources can emit incoherent radiation or coherent bands of amplificated radiations (i.e. LASERs). Considering UVR, among the main applications relevant for occupational exposure there is the use of UV as sterilizing agents for both surfaces and products, the idustrial processes applying UV rays in the machineries for photo-lithography and printing, the medical applications as e.g. the photo-therapy for the neonatal jaundice, the UV emissions during welding processes, and many others. Also visible light is emitted during welding, and of course it is used for illumination purposes: kind of intense exposures can be possible in the entertainment sector, e.g. in theatres or in television studios, in shopping centers, and in general where it is required to be close to sources emitting intense lights (indicators, signals, LED, projectors, etc). Also visible light is used for industrial, e.g. printing processes, and medical applications, e.g. for photopolymerization of the materials used in dental clinics. Finally, infrared radiation is also emitted during welding activities, and moreover it is emitted as a result of industrial processes generating very high themal energies during the treatment of metals, glass and other materials. Furthermore, IR-based technologies are widely applied e.g. in communication and surveillance systems [4]. LASER technologies can use all the optical radiations. Gas LASERs, as those using argon or krypton, mainly amplify UV or short wavelength visible light, while solid state LASERs, as neodymium YAG LASERs, and semi-conductor LASERs, as those using gallium, mainly amplify infrared or long wavelength visible light [4].

Even if the number of artificial sources emitting OR at the workplaces is huge, the effective number of workers exposed to levels potentially determining relevant health risks is relatively limited, as frequently the sources are appropriately shielded [4–7]. A possible exception is represented by welding activities: welders should be appropriately protected, with adequate clothing and face masks with eye filters for the specific bands of ORs emitted during the welding process [4–6, 8]. For the other sources of artificial OR the major problems may occur in case of malfunctions of the machineries with failures of the protection mechanisms, and/or of workers with inadequate protections, determining work-related accidents possibly causing severe damages [9, 10]. The eye is one of the most frequently involved organ, in particular in these cases [11, 12].

On the other hand, the most important source of occupational exposure to OR, in terms of both the numbers of exposed workers and relevancy of possible adverse effects, is certainly the Sun. Millions of workers have an exposure to solar radiation (SR) worldwide: among the main job categories involved there are farmers [13, 14], construction workers [15–17], fishermen [18], lifeguards [19, 20], gardeners [21, 22], ski instructors/mountain guides [23, 24] and others [25, 26]. These workers, spending a significant part of the working day outside, are collectively identified with the term of “outdoor workers”. Fortunately, SR at the Earth' surface does not include all the components of OR spectrum, and in particular all UVC rays and the large majority of the UVB are blocked in the stratosphere [5, 26]. As UV radiation is a carcinogenic agent, also SR is considered a carcinogenic exposure [27]: it is estimated that SR represents the occupational carcinogenic exposure with the highest amount of workers exposed [28].

2.2. Interaction mechanisms with biological tissues and main effects of optical radiation exposure

OR have a quite low ability of penetrating the biological tissues, and therefore the main targets are the eyes and the skin [5, 26]. Two main mechanisms of interaction with the biological tissues can be identified for OR bands:

- Thermal mechanisms: these effects are typical of IR and of long wavelength visible light, and they are related to the conduction of heat in the tissues, usually requiring intense exposures. In case of insufficiently intense exposure no appreciable effects can be determined, as the heat is dissipated through the surrounding tissues [29]. Accordingly, usually only acute effects, resulting in eye injuries or skin thermal burns can be associated to infrared or visible light exposure with thermal mechanisms [29], even if, mainly in the past, some chronic skin alterations [30] as well as thermal cataract have been reported [31, 32].
- Photo-chemical effects are possible in case of exposure to UVR and to short wavelength visible light [5, 26]. Photons are absorbed by specific targeted molecules (i.e. chromophores) in the biological tissues, releasing energy and inducing chemical reactions, with consequent damages and alterations (e.g. inflammation) [5, 26]. Photochemical effects are possible both in case of short-term intense exposures but also as a consequence of long-term less intense exposures [33].

The most hazardous component of OR is UVR: UV rays have higher energy compared to infrared and visible radiation and they act with photochemical mechanisms, causing both acute and chronic effects in humans [5, 26]. After intense short-term exposures, acute skin effects as skin erythema and photodermatoses, in case of presence of a photo-toxic substance (e.g. a topic drug or a cosmetic) on the skin, can occur (it should be noted that photodermatoses may be also associated with some wavelenghts of visible radiations) [5, 26]. Also photochemical burns of the unprotected eyes are possible, especially in case of intense direct exposures or indirect exposures from surfaces with high reflectance (e.g. snow, polished metals): UV rays can be highly absorbed in the ocular surface, causing an acute inflammation of the cornea and of the conjunctiva called photokeratitis/photoconjunctivities, determining photophobia, redness, pain, burning, tearing and foreign body perception [5, 12, 26].

Considering long-term exposure, UVR is able to induce various skin and eye effects, many of them very severe. UVR is mutagenic for the DNA and cumulative damages over time can induce pre-cancerous and cancerous alterations [5, 26, 27]. In the skin chronic UVR exposure is able to induce photoaging, i.e. a progressive process including functional and aesthetic skin changes with loss of elasticity, cell depletion, pigment accumulation and substitution of normal tissue with fibrous tissue. considered to be a precancerous alteration [5, 26, 34, 35]. Other pre-cancerous lesions, sometimes identified also as *in situ* carcinomas, induced by chronic UVR exposure of the skin are actinic keratoses (AK). AK are disorders of the keratinocytes resulting in thickening of the skin with formation of scaly and/or crusty lesions. Untreated lesions have up to a 20% risk of progression to squamous cell carcinoma (SCC) [5, 26, 27, 35, 36]. In addition to pre-cancerous lesions, UVR is able to induce skin cancers. The most common are the basal cell carcinoma (BCC) and the SCC of the skin, also called as keratinocytes cancers [26, 27, 37]. These tumours are the most frequent malignancies in subjects with fair skin, and accordingly they are the most frequent type of cancer in Europe, Canada, US and Australia. Fortunately these tumors have mainly a local malignancy, resulting only seldom in methastatization processes: accordingly, the prognosis is quite good compared to other tumors, and, if treated in time, the mortality is low, but they can result in quite impressive mutilations, especially considering that they usually appear in solar UV exposed skin areas, as the face [38, 39]. Both BCC and SCC are somehow related to cumulative UVR exposure and there is evidence that outdoor workers have a relevantly increased risk of getting these tumors [40], while only few reports of associations with artificial UVR exposure at work are available [41]. Another skin tumor related to excessive UVR exposure is the malignant melanoma (MM), a cancer originating from the skin melanocytes. MM are less frequent compared to BCC and SCC, but they often methastatize if not diagnosed in time, determining an important burden not only in terms of disability adjusted life years (DALYs) but also in term of mortality [27, 42]. Considering occupational exposure, the relation with SR exposure in outdoor workers is controversial, as some studies reported a possible protective effect of cumulative UVR exposure, while the increased risk of MM is associated with intense exposure in the childhood with repeated sunburns [27, 43]. Some studies reporting a possible increased melanoma risk for welders have also been published [27, 41].

Considering now possible long-term effects in the eyes, UVR can induce chronic alterations of the ocular surface, being absorbed mainly in the cornea and in the conjunctiva, determining a chronic inflammatory stimolous and pathological alterations with abnormal growths of the corneal and conjunctival cells [5, 26, 44]. This may result in various diseases, some of them representing mainly aesthetic alterations with no clinical relevancy, as pinguecula, other more severe with potential affection of the visual function if not treated, as the pterygium, an abnormal growth of the conjunctiva from the nasal angle of the eye to the center, finally covering the cornea [44, 45]. Corneal and conjunctival squamous cell carcinomas (i.e. the same types of cancers occurring in the skin) are also possible: fortunately they are very rare, but with demonstrations of associations with UV exposure [44]. Moreover, also another eye tumor, the melanoma of the eye, more frequent compared to corneal and conjunctival carcinomas, even if still quite rare, has been reported as possibly associated with UV exposure, in particular in welders [44, 46].

Furthermore, a relevant quote of UVR is able to penetrate the ocular surface being absorbed in the lens [5]. There, with photo-oxidation damages contributing to the age-related process of the denaturation of the lens proteins, UVR can accelerate and increase the opacification of the lens [47]: it is estimated that more than the 20% of the cataracts can be attribued to excessive UVR exposure [48], and it should be noted that cataract is still the main cause of blindness worldwide [49]. Not only solar radiation, but also artificial UVR is associated to an increased risk of cataract development [47, 50].

Finally, another possible chronic adverse eye effect that can be associated in particular to long-term SR exposure is macular degeneration, a very frequent multi-factorial degenerative disease of the central part of the retina, currently the third among the major causes of blindness worldwide [49]. Scientific demonstrations of the relation between this eye pathology and SR exposure are mainly epidemiological, rather then experimental, but some hypothesis have been proposed [51]. In this case, the role of UVR is limited to that of a small portion of UV-A radiation, able to reach the retina especially in younger subjects when the lens is more transparent [5]. But also violet/blue visible light can contribute to a chronic photochemical retinal damage through photo-oxidations [52, 53].

3. Prevention of the health risk related to occupational optical radiation exposure

3.1. Occupational optical radiation exposure risk in the workplaces and workers belonging to particularly sensitive risk groups

Currently in Europe there are no specific obligations for the HS of workers exposed to solar radiation, even if, considering the relevancy of the risk and of the adverse health effects to be expected, in many countries an increasing attention to the protection of outdoor workers against UVR and to the occurrence of solar UV-induced occupational diseases has been raised in recent years [5, 26, 38, 54–59]. One of the issues still to be solved is the lack of a recognized occupational limit for solar UVR exposure at work in Europe: the recognition of such a limit would be helpful to implement risk evaluation processes in the workplaces, defining the specific protections needed. On the other hand, since 2006 a specific European Directive "2006/25/EC" for the prevention of the occupational risk related to artificial optical radiation exposure has been emplaced [4]. In this case, specific occupational exposure limits to be respected are available, and moreover the Directive requires mandatory risk evaluation, definition of technical and organizational preventive measures, specific training of the workers, the forniture of adequate personal protective equipment and, if needed, an appropriate health surveillance.

For all the previously mentioned steps of the process for an adequate prevention of OR risk at the workplaces, the Directive indicates that a special attention has to be deserved to the workers "*belonging to particularly sensitive risk groups*" [4]. No specific indications are included in the EU Directive helping in identifying these workers. We report here below a non-exhaustive list of possible conditions determining a particular susceptibility to OR exposure, increasing the risk of adverse effects, mainly for the eye and the skin, and requiring a special attention [4, 5, 26].

- Conditions related to a possible increased risk of adverse skin effects (mainly related to the UVR component of OR): e.g. albino subjects and all the workers with fair skin photo-types (i.e. at least Fitzpatrick skin photo-type 1 or 2 [60]), who are at an increased risks for developing all the UV-related acute and long-term skin effects; workers affected by skin diseases that can be photo-induced or photo-aggravated, as psoriasis or xeroderma pigmentosum; workers being diagnosed with precancerous or cancerous skin lesions; workers being treated with photosensitizing drugs or in contact with photosensitizing substances as psoralenes.
- Conditions related to a possible increased risk of adverse eye effects: workers with alterations of the eyes structure possibly affecting the quantity of OR absorbed in specific eye regions, as e.g. iris alterations (as coloboma, aniridia), pupil alterations (as tonically dilated pupil, mydriasis), lens alterations (aphakia, artificial intraocular lens); workers being diagnosed with eye diseases possibly being worsened by excessive OR exposure, as e.g. initial lesions of the lens (as presence of small lens opacities or cataract at an initial stage) or of the retina (as the presence of drusen in the macula); subjects with only a monocular vision, as the possible occurrence of OR-related adverse effects in the eye may result in blindness.
- Other conditions: pregnant workers are usually considered among the workers belonging to particularly sensitive risk groups, mainly considering (but not limited to) the possible thermal effects of the infrared component, increasing the body temperature in the abdominal region; underage workers can be also potentiually included, especially considering that the lens is more transparent to UVR, possibly enabling a higher amount of radiation reaching the retina.

3.2. Health surveillance of workers exposed to optical radiations

According to the current European legislation, there are two possible scenarios for the HS of OR exposed workers. The HS is an obligation in case a relevant risk is evaluated in the workplace according to the EU Directive 2006/25/EC for artificial OR exposure, both in case of incoherent sources and of LASER use. On the other hand, considering SR exposure risk of outdoor workers, currently in Europe HS is not mandatory [5, 26], even if, in the light of the numbers of outdoor workers, the high levels of occupational UVR exposure detected in several studies [13–26] and of the documented increased risk for these workers of developing UVR-induced eye and skin effects [25, 26, 40, 44–48, 50, 51, 54, 55, 27, 28, 34–39] an appropriate HS seems absolutely necessary.

The objective of the HS of OR-exposed workers is the prevention and the early diagnosis of adverse effects, mainly of the eyes and of the skin. During HS activities, specific attentions have to be deserved to the workers affected by conditions inducing a particular susceptibility to the risk, as the ones mentioned here in the previous section 3.1. HS programs usually include both pre-employment and periodic medical examinations from trained occupational physicians, who may require, on individual basis, supplementary health controls possibly encompassing other specialists involved in the specific problem detected (e.g. ophthalmologists, dermatologists, etc) [26, 38, 59]. As stated above, the most alarming health risk to be considered during HS is the one related to the UVR component that can induce relevant adverse health effects as skin cancers, currently the most frequent tumors among Caucasian subjects. These cancers, together with other OR-induced eye and skin pathologies, are recognized occupational diseases in many European countries, but not in all [38, 59]. Nevertheless, these cancers are largely underreported: an extension of the HS also to outdoor workers should help in increasing the reporting of OR-induced occupational diseases, allowing workers to receive an adequate medical care and compensation for the diseases, and letting institutional authorities and governments acknowledged of the true magnitude of the phenomenon, and consequently of the need of preventive measures [38, 55, 59].

4. Electromagnetic fields: occupational exposure and health effects

4.1. Occupational exposure to electromagnetic fields

Nowadays, a certain level of EMF exposure is present in almost all the working environments, and there is an extremely large, and increasing, variety of occupational EMF sources. Accordingly, some exposure to EMF is present for almost all workers. But, on the other hand, numerous sources are present also in the general environment. Accordingly, it can seem inappropriate to consider every single worker as an "*exposed worker*". A detailed discussion on this topic is beyond the scopes of this article but, in general, it can be considered appropriate to evaluate as "*exposed*" workers, those with an expected EMF exposure above the levels usually detectable for the general population at home and in public places [61–64]. A peculiar aspect in this context is that in some workers with a particular susceptibility (*"workers at particular risk"* - WPR), also EMF levels permittable for the general public may determine a non-irrelevant residual health risk. This is specifically the case of workers with active implanted medical devices (AIMD), who may be at risk for interference problems when in proximity of an EMF source [65–67]: these aspects will be discussed in detail in the next paragraphs.

When dealing with the problem of occupational exposure to EMF, as it happens also for OR, it is important to identify the specific types of EMFs emitted by the considered sources, as different regions of the EMF spectrum have different biological interaction mechanisms and, consequently, different effects, depending on the frequency bands. For the objectives of this article, we adopt a simplified EMF classification, discussing here the main issues related to the exposure in particular to static magnetic fields (SMF, frequency= 0 Hertz), extremely-low frequency magnetic fields (ELF-MF, frequency= 1 - <300 Hertz), intermediate frequency EMF (IF-EMF, frequency= 300 Hertz - <100 kilohertz) and high frequency EMF (HF-EMF, frequency> 100 kilohertz, including radiofrequency - RF -, microwaves, millimeter and terahertz waves) [61–64, 68]. Considering now specific working situations and occupational sources with potentially relevant emissions of EMF, a useful guide for the prevention of EMF risk at work is the so-called "*non-binding guide*" for the application of the European Directive 2013/35/EU [68]: we present here an extract of the document with a list of work activities and EMF-sources determining occupational exposures (Table 1).

Table 1: Non-exhaustive list of work activities/occupational sources inducing a potentially relevant exposure to electromagnetic fields extracted from the "non-binding guide" for the application of the European Directive 2013/35/EU

Type of equipment or workplace
Construction: various equipment and machineries (e.g. concrete mixers, cranes, vibrators, welding machines, etc)
Electrical supply: electrical installations, generators, inverters
Infrastructure (buildings): base station antennas
Infrastructure (grounds): garden appliances
Heavy industry: industrial electrolysis, furnaces, arc melting, welding machines
Light industry: arc welding processes, dielectric heating and welding, industrial magnetizer/ demagnetizers
Medical: magnetic Resonance Imaging (MRI), other medical equipment using EMF for diagnosis and treatment (for example, short wave diathermy, transcranial magnetic stimulation)
Office: audio-visual equipment containing RF-transmitters, office equipment (e.g. photocopiers, electric staplers, paper shredders)
Transport: motor vehicles and plants, radars (air traffic control, military use, weather monitoring, long range radars), electrically driven trains and trams
Wireless communications Cordless phones (including base stations for cordless phones), mobile phones, wi-fi routers

It should be noted that for the sources and the occupational activities with potentially relevant occupational EMF exposures presented in the Table 1 no specific frequencies ranges of EMF emissions are reported. This is because in many cases the exposure can include various EMF bands, as e.g. in welding activities, where ELF, IF-EMF and RF can be represented in the specific emission spectra depending also on the type of welding procedure, or in MRI activities, where operators are exposed to the action of the SMF as well as to time-varying EMF when they move within the SMF, while the patients are also exposed to RF when the scanner is in function. In other cases, the EMF exposure can be referred to specific EMF bands, as e.g. for electrical installations, generators and inverters, emitting mainly in the ELF range, or for wireless communication systems, with emissions mainly in the RF band [61–64, 68–70]. Another relevant note for an appropriate interpretation of the Table 1 is that not all the potential exposures listed represent, in normal conditions, a relevant risk for the workers; e.g., again in the case of wireless communication systems or in the case of office equipment, the listed sources may determine an occupational risk only for workers with an increased susceptibility to the EMF risk, as subjects with AIMD who have to work close to the sources [61–68], as previously introduced. On the other hand, other sources can be able to usually induce high exposure levels, potentially representing an occupational risk in case of inadequate working conditions, e.g. in the case of close proximity of operators to a MRI scanner, in industrial electrolysis plants, or in working activities involving induction heating systems, soldering devices, or broadcasting systems and devices, etc. [61–64, 68].

4.2. Interaction mechanisms with biological tissues and main effects of electromagnetic fields exposure

According to the above mentioned European Directive 2013/35/EU, currently in Europe for the prevention of the occupational risks related to EMF exposure only effects based on recognized interaction mechanisms with the biological tissues are considered [68]. The EU Directive indicates specifically the short term direct biophysical effects and the indirect effects related to EMF exposure [68]. A necessary punctualization here, considering the quite large number of studies dealing with suggested long-term effects related to EMF (among the main examples there are the suggested associations between leukemia and ELF-MF exposure, and brain cancers with RF exposure), is that, for these effects, the current European legislation does not consider sufficient the available scientific evidence, in particular considering that no adequate pathogenetic mechanisms in humans have been demonstrated [61–64, 68]. The position of the EU Commission is coherent with the opinions of various recognized national and international organizations and institutions [61–64, 71-85].

According to the above mentioned EU approach, we discuss here only: a) direct biophysical effects caused in the human body by its presence within an EMF; and b) indirect effects, induced by the presence of an object in the EMF (object that can also be placed inside the body, as in the case of implanted medical devices) [68].

According to the frequency band of the EMF, different mechanisms are involved for the occurrence of direct effects: non-thermal mechanisms for static and low-frequency fields, and thermal mechanisms for high frequency fields. For the intermediate frequencies both the mechanisms are possible [61–64, 68]. Among non-thermal effects, based on cuurents induction in the biological tissues, there are the following: limb currents, stimulation of muscles, nerves or sensory organs with induction of temporary annoyance or with a possible detrimental effect on cognition or on other brain or muscle functions, with possible risks for the safety of the workers [68]. Considering thermal mechanisms, the direct effects, related to HF-EMF exposure, and possibly to IF-EMF, are related to an increase of the temperature in the body, that can be usually more relevant at the surface, and accordingly in targets as the eyes, where very intense HF-EMF can theoretically induce a thermal damage of the lens with opacification (cataract), and the skin, where thermal burns can be possible, also in this case after very high exposures levels [64, 68]. A further classification of direct effects according to the 2013/35/EU Directive is the one concerning *"sensory"* and *"health effects"* [68]. Sensory effects are usually rapidly reversible and transient. They can be considered non-pathological effects, usually with no consequences for the individuals, even if they can be associated with an increased risk of work accidents. Sensory effects are mainly related to relevant SMF and ELF-EMF exposures, representing the consequence of an induction of currents, stimulating the nervous systems and/or sensory organs. Examples of sensory effects are vertigo, nausea, perception of a metallic taste in mouth after SMF exposure, magnetophosphenes (i.e. eye lamps perception) and minor reversible changes of some brain functions (e.g. attention, congnitive function) in case of ELF-EMF exposure [61–63, 68]. On the other hand, EMF-related *"health effects"* represent severe alterations, that usually appear only in case of overexposure to EMF, significantly above the occupational limits established e.g. in Europe by the 2013/35/EU Directive. A non-exhaustive list of these health effects, based on non-thermal mechanisms for SMF and ELF-MF (an example can be an alteration of the cardiac rythm) and on thermal mechanisms in case of very intense HF-EMF exposure (e.g. skin burns), is presented in the Table 2. As stated above, for IF-EMF exposure sensory and health effects typical of both low and high frequencies can be possible [61–64, 68].

Table 2: Non-exhaustive list of health effects caused by overexposure to electromagnetic fields, based on the European Directive 2013/35/EU

EMF type	
Static magnetic field	Alterations of the blood flow in the limbs; alterations of the brain functions; alterations of the cardiac rhythm and of the cardiovascular fuction
Low frequency fields	Pain and/or tingling sensations due to an involuntary contractions of the muscles or to the stimulation of the nervous system; alterations of the cardiac rhythm
Intermediate frequency fields	The effects of both high and low frequencies can be possible
High frequency fields	Excessive increase in temperature and/or thermal burns over the whole body or in specific areas; thermal damage of the eyes (possibility of thermal cataracts), skin, testicles

Considering now indirect effects, these effects can occur, as stated above, when there is an object inside the EMF, together with the human body. All the EMF frequencies can be involved, and, as in the case of medical devices, it should be noted that the object can be also implanted in the human body [68]. Some of these indirect effects mainly represent a risk of work-related injuries: EMF can initiate electro-explosive devices causing fires and explosions. Other indirect effects possibly associated to severe injuries are contact currents, that can be induced in the body by the contact with charged objects within an EMF [68]. The most relevant indirect effects that can happen also in case of usual exposures, and not as a consequence of a malfunction/wrong procedure, are interference problems of EMF with implanted or body worn devices, usually for medical purposes. The major problems can be experienced in case of active devices, as pacemakers or implantable cardioverter defribrillators (ICD): their functions can be altered by the EMF, determining a risk for the workers' health [61–68]. Also, passive devices, as e.g. metal splinters or graft, can be affected by EMF: in particular, SMF may dislocate the devices made of ferromagnetic materials, causing inflammation or other problems in the surrounding tissue. Moreover, IF-EMF and HF-EMF can determine a heating of the metallic parts of the devices, also in this case with a potential damage to the biological tissue [65–68].

5. Prevention of the health risk related to electromagnetic fields exposure

5.1. Occupational electromagnetic fields exposure risk in the workplaces and workers at particular risk

In Europe, the prevention of the occupational risk related to EMF is regulated according to the Directive 2013/35/EU. As it happened also for OR, a specific *"non binding guide"* was then produced by the European Commission, to give practical indications for the application of the Directive [68]. The Directive requires mandatory EMF risk evaluation in the workplaces, defining the technical and organizational preventive measures to be applied, including a specific training of the exposed workers, the adoption of adequate personal protective equipment and, if needed, an appropriate health surveillance. Specific occupational exposure limits are available for the different EMF frequencies, mainly based on the guidelines of the International Commission on Non-Ionizing Radiation Protection (ICNIRP) [61–63]. Different limit values are available not only according to the EMF frequency, but also based on the different effects to be prevented: separate limits for the prevention of the above-mentioned *sensory* and *health effects* are defined in the EU Directive [68]. As previously introduced, the possibility to reach exposure levels able to induce *health effects* is very rare, happening only in case of overexposure, e.g. in case of accidents. Moreover, it is not sufficient to simply exceed the limit value to induce the appearance of a *health effect*, as usually exposures highly above the limits are needed. Furthermore, also the exceeding of the limits for *sensory effects*, much lower compared to the limits for *health effects*, is not usual, and in principle it has to be avoided in normal conditions [86, 87].

Considering this, one of the main problems for the prevention of the occupational EMF risk is the possible presence at the workplace of WPR, as defined by the Directive 2013/35/EU, for whom the occupational limits set might be not fully protective [68]. Currently, a non-exhaustive list of WPR for EMF exposure includes:

- Workers with active implanted medical devices (AIMD): e.g. pacemakers, implanted cardioverter defibrillators, ear implants, neurostimulators, implanted drug infusion pumps, etc [65–68, 88, 89].
- Workers with passive implanted medical devices containing metals: e.g. artificial joints, plates, surgical clips, stents, heart valve prostheses, intra-uterine devices, etc [68, 88–91].
- Workers with body-worn devices: e.g. drugs infusion pumps, hearing aids, continuous glucose monitoring systems, etc [68, 88, 89].
- Other WPR categories included in the EU Directive: pregnant workers [68, 88, 89].

5.2. Health surveillance of workers exposed to electromagnetic fields

According to the Directive 2013/35/EU, HS of EMF exposed workers is mandatory, when a relevant risk for the workers is evaluated. Moreover, for the HS, as well as for the risk assessment, the problem of the WPR has to be specifically taken into account [68, 89]. As defined in the Introduction, HS is aimed at identifying any abnormality possibly associated to a recognized work related risk in exposed workers [3]. All the investigations chosen for HS have to be proved with an appropriate level of scientific evidence: the contents of the HS can include biological tests and other investigations, when they are chosen for their validity and relevance with respect to the occupational risks, avoiding investigations that don't fulfill these criteria [92]. Considering the specific case of EMF exposure, a reliable application of these criteria may involve some possible issues. In fact, according to the EU Directive the scopes of the HS are the prevention and early detection of the previously defined direct biophysical effects, including the sensory ones (as e.g. the presence of vertigo or of nausea associated to EMF exposure, etc.), based on non-thermal and thermal mechanisms [68]. In general, these effects do not appear for occupational exposure levels below the limit values, as they can be induced only as a consequence of excessive exposures to quite high levels of EMF [86, 87]. It has also to be highlighted here that sensory effects, that are fully reversible and transient, cannot be considered an actual health risk for the workers [93–95], even if some data suggest a possible association with an increased risk of work-related injuries for the exposed subjects [96, 97]. The other main purpose of the health surveillance related to the occupational EMF risk is the prevention of indirect effects, and this specifically involves the identification of the WPR. Among the conditions of particular susceptibility, probably the main issues are related to possible electromagnetic interference (EMI) problems with AIMD. EMI can appear also as a consequence of kind of low exposure levels if a susceptible subject with an AIMD is close to an EMF-source, and the interference can impair the fundamental functions of the devices [61–68].

Considering this, the health surveillance criteria to be considered should mainly address the identification of possible medical signs and symptoms of sensory effects and of the conditions of particular susceptibility to the EMF-risk, typical of the WPR. For these purposes, particular lab tests or other specific clinical investigations are not required on a routine basis, while their opportunity can be judged by the occupational physician on an individual basis after a medical examination. Useful instruments to be periodically administered to the workers are the questionnaires evaluating symptoms and conditions of particular susceptibility [93–95]. When administering questionnaires, important prerequisites are a validation process [98] and a preparation of the tool based on scientific results: unfortunately, to the best of our knowledge, to date there are no examples of questionnaires specifically designed for an application during HS examinations of EMF-exposed workers. A further note to the problem of the EMF-related HS is that, in general, medical examinations for workers in good health conditions, with no conditions of particular susceptibility and working in environnments where the EMF levels are supposed to be low or very low (e.g. offices) have not to be considered as activities to be periodically repeated. In these cases, only a single medical investigation performed before the starting of the job, with an effective information on all the conditions possibly determining a particular susceptibility to the EMF risk (NB: the information has to be periodically repeated in these cases, while the medical examination doesn't), seems advisable for an adequate prevention [68, 89].

Finally, a peculiar situation explicitly mentioned in the EU Directive is the case of an *"extraordinary"* HS of the EMF exposed workers, needed when *"any undesired or unexpected health effect is reported by a worker"* or *"in any event where exposure above the ELVs* (i.e. exposure limit values) *is detected".* In these situations, an appropriate *"medical examination"* needs to be provided to the workers [68]. Also, in this case, no guidelines or evidence-based indications are available to define valid contents for these medical examinations. Furthermore, as previously noted, situations with exposure levels exceeding the limits do not necessarily result in the occurrence of adverse health effects [86, 87]. Also, in this case, the main problems should be expected for the WPR. Accordingly, both for extraordinary and routine HS the contents of the examinations include an appropriate in-depth medical examination of the workers by an occupational physician with an adequate competence in the field, administrating specific questionnaires to collect information on suspected EMF-related symptoms and possible conditions of particular susceptibility to the risk, eventually integrated by specific medical consultations and/or laboratory tests and/or diagnostic exams to be decided on an individual basis, considering the types of EMF frequency involved, the exposure level, the susceptibility of the workers and the expected effects to be evaluated [68, 89].

6. Conclusions

Occupational NIR exposure, including EMF and OR, is almost ubiquitous: in principle, an evaluation of the occupational health risk should be appropriate in all workplaces. Based on the health risk assessment, HS programs for the exposed workers have to be established, with the objective of preventing or, at least, identifying at an early stage the possible health effects associated with the exposure. Both risk evaluation and HS activities have to specifically consider the possible presence in the workplace of "workers at particular risk", who deserve a specific attention, as they have an increased susceptibility to the risk. The HS needs to be performed by occupational physicians with adequate and updated skills in the prevention of NIR risk, and accordingly with an appropriate specific training in this field. Here below we present a conclusive summary of the main relevant points to be considered for the health surveillance of NIR exposed workers:

Optical radiation:

i. Occupational physicians have to consider that the exposure can be associated to both artificial and natural sources. In particular, solar radiation is certainly the main occupational exposure source, even if sometimes under-recognized as a specific occupational risk.

ii. The main target organs of optical radiation exposure are the eyes and the skin.

iii. For the prevention and early diagnosis purposes, the possible occurrence of both short-term and long-term eye and skin effects, respectively related to acute and cumulative exposures, has to be adequately considered as a fundamental criterion of HS.

iv. The most harmful component of optical radiation is UVR, able to induce both acute and long-term effects with photochemical mechanisms; among the most severe adverse effects related to chronic UV exposures there are skin cancers, i.e. the most frequent forms of neoplasms in Caucasian subjects. Other diseases identified in UVR exposed workers are: skin erythema, photoaging and actinic keratosis for the skin, photokeratoconjunctivitis, pterygium, lens opacities and possibly macular degeneration for the eyes.

v. During HS activities, specific conditions of particular susceptibility for the exposed workers have to be considered: e.g. a fair skin phototype, eye alterations as aphakia, and others.

vi. Optical radiation related adverse effects are recognized "occupational diseases", even if frequently underreported: physicians have to notify the occurrence of these diseases in exposed workers to the specific workers' compensation Authorities in their Country.

Electromagnetic fields:

i. According to the European legislation, the recognized effects related to EMF exposure to be considered for the health surveillance of the workers are short-term direct biophysical effects and indirect effects.

ii. Direct effects can be related to both non-thermal and thermal mechanisms, and they are usually induced only by high exposures.

iii. Indirect effects, as the electromagnetic interference with AIMD, can occur also as a consequence of lower exposure levels.

iv. To date, there are no agreed and shared criteria for the health surveillance of EMF-exposed workers, and in particular there are no evidence-based indications on the appropriate contents and procedures for the medical examinations to be performed for the monitoring of the health status of the exposed subjects.

v. The trained occupational physicians have to evaluate all the possible symptoms related to the sensory and health effects of EMF exposure, considering specifically the type of frequency, the exposure level and the mechanisms involved.

vi. One of the most important activities during health surveillance is the screening of all the conditions that can induce a particular risk for the exposed workers, as e.g. AIMD: a check for the presence of these conditions needs to be done before the employment by the physician, and an extensive information on these conditions has to be provided to the workers, and periodically repeated.

vii. In case of overexposure situations or in case of workers reporting symptoms associated to the EMF exposure, an appropriate medical examination has to be provided to the workers, with specific contents to be evaluated on an individual basis, again based on the type of EMF-frequency, on the exposure level detected and, on the mechanisms, involved.

Conflict of Interest

The Authors declare no conflict of interest.

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