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Practical aspects of occupational EMF exposure assessment

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Abstract Electromagnetic fields exposure assessment methodology is briefly presented. The basic problems defined for the practical use of electromagnetic fields measurements and numerical calculations carried out for workers exposure assessment in real occupational situations are discussed. The examples of data from real workplace are presented, focusing: spatial distribution of electromagnetic fields affecting worker's body, complex characteristics of the frequency content, workers activities/ moving in the workplace, field impedance, etc. The situation when the use of calculations is required is discussed. The basic requirements for workers exposure assessment protocols are presented. The possible range of the use of internal and external measures of exposure level is also discussed.

Keywords EMF exposure · Exposure assessment · Work place · Measurements · Numerical calculations

1 Introduction

The majority of population is subject to simultaneous exposure to electromagnetic fields (EMF) from broadcasting and power distribution installations, as well as various electrical appliances. Characteristics of EMF in the workplace is often very specific in comparison with the fields from general public environment. In the work place the locations of the EMF source against worker's body can change significantly. The geometry of the source, frequency and level of EMF produced by it can also be unstable. Workers exposure level can be high, even exceeding international safety guidelines.

EMF's exposure assessment adequate to the real exposure level is the crucial step towards appropriate risk assessment for occupational safety and health (OSH) engineering, epidemiological studies of EMF-exposed groups, environmental monitoring. The strongest demands for the use of detailed EMF exposure assessment protocol come from the legislations concerning mandatory control of occupational or environmental EMF exposure, e.g., European Directive on workers EMF exposure limitation (Directive 2004/40/EC) or national legislation on occupational safety and health (Karpowicz et al. 2006). Presented review on practical aspects of occupational exposure assessment based on our experience got from research and routine EMF assessment in the work environment.

2 EMF in the work environment

Electric and magnetic field strengths are so-called vector quantities, characterized by the direction of the vector and its module, expressed by a square root of the sum of all squared components. Electric field strength, E, is expressed in volts per meter (V/m), and magnetic field strength, H, is expressed in amperes per meter (A/m).

Physical properties of EMF are changing with the distance from the source (Koradecka and Karpowicz 2006). In the area called far-field, the plane-wave model can represent EMF propagation: wave fronts have a planar geometry, E and H vectors and the direction of propagation are mutually perpendicular, the phase of the E and H fields is the same and the ratio of E/H amplitudes (impedance of the

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field) is constant throughout space (E/H = 377 ohms in free space).

The characteristic of EMFs in near-field area existing in the vicinity of the source is more complex: the maxima and minima of E and H fields do not occur at the same points along the direction of propagation, EMFs structure may be highly inhomogeneous and there may be substantial variations from the plane-wave impedance of 377 ohms (both an almost pure E field or H field are possible).

EMF affecting workers are usually so-called near fields, always in the case of exposure to EMF of low or intermediate frequency range (LF, IF) and usually in the case of radiofrequency (RF) exposure in the vicinity of source. The impedance of such fields depends on electrical characteristics of the EMF's-source-worker's-body system. Electric voltages and currents in the electric EMF source play important role, but direct coupling between worker's body and EMF source can significantly modify the exposure conditions.

The sources of high level of magnetic field exposure to time-varying fields are basically: welding devices and industrial induction heating devices, strong exposure to static magnetic fields is associated with nuclear magnetic resonance device (magnetic resonance imaging scanners and spectrometers) (Gryz and Karpowicz 2000; Korniewicz et al. 2001). Significant exposure to electric component can be found in practice in the vicinity of high voltage power distribution systems or electro surgery devices. The most complicated situation can be found, when both components (E and H) should be consider, especially when the field impedance can varying significantly during the application, as in the case of some electro surgery use. Exposure to EMF from broadcasting and microwave heating devices usually can be assessed following E component.

3 EMF exposure assessment

Frequency-dependent two-step exposure limitations were published by international bodies (ICNIRP, IEEE, European Commission):

- limitations concerning ''internal measures'' of exposure effects occurring in an exposed body, define maximum permissible exposure conditions,
- limitations concerning ''external measures'' of exposure level, determining environmental conditions of exposure which require special attention (e.g., inspection measurements, exposure evaluation, workers' training).

Internal measures cannot be directly measured in the real environment. External measures can be directly measured in the workplace and are intended for practical use. International EMF exposure limitation documents (ICNIRP 1998; IEEE 2002, 2005; Directive 2004/40/EC) refer to the following internal measures of effects occurring in the exposed body:

- current density, J, in the frequency range up to 10 MHz,
- in situ electric field, E, in the frequency range up to 3,350 Hz,
- specific energy absorption rate, SAR, in the frequency range 100 kHz–10 GHz,
- specific energy absorption, SA, for pulsed fields in the frequency range 300 MHz–10 GHz.

The following external measures are derived from relevant internal measures using measurement and/or computational techniques: electric field strength (E), magnetic field strength (H), magnetic flux density (B), power density (S), contact and induced currents flowing through the limbs (I).

Compliance with the permissible values established for external measures' quantities ensure compliance with the relevant internal measures. If the measured or calculated value of a particular external measure exceeds its permissible level it does not necessarily follow that the internal measures will also be exceeded. Whenever the level of an external measure is exceeded, it is necessary to test compliance with the relevant internal measure and to determine whether additional protective measures are necessary in the workplace.

4 EMF measurements and protocol for assessment of workers exposure

In the typical situation the process of occupational EMF exposure assessment is composed of the following basic steps:

A—EMF characteristic identification,
B—selection of EMF assessment criteria,
C—selection of measurements protocol,
D—selection of measurements device,
E—measurements execution,
F—analysis of the results of measurements,
G—interpretation on the EMF level of exposure conditions under assessment,
H—decision on the need for further action.

4.1 *Step A*—EMF characteristic identification

Sufficient identification of characteristic of the EMF (e.g., frequency composition, spatial distribution) in the workplace (*Step A*) is the one of the most important actions for the process (Fig. 1). Any mistake at this step can totally destroy the EMF assessment process and results in many-fold

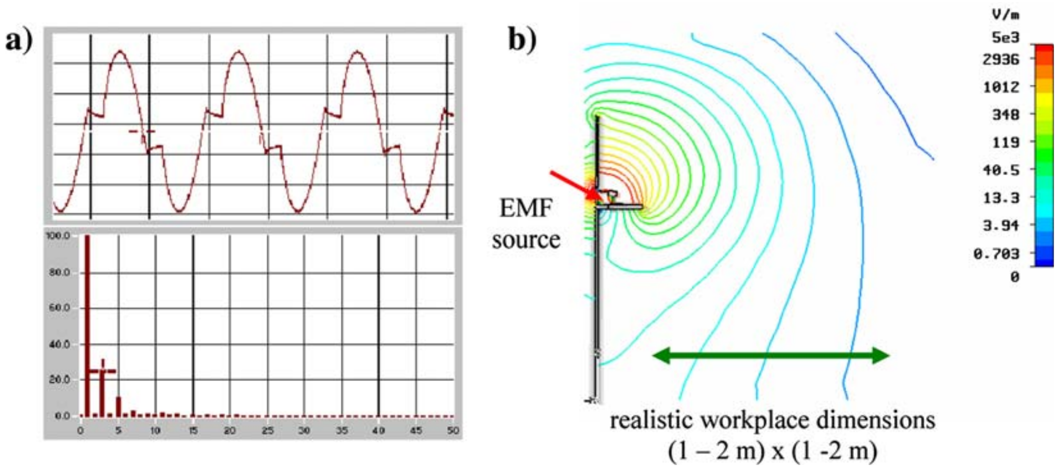

Fig. 1 Examples of selected parameters of EMF: (**a**) spectrum of frequency components of magnetic fields produced by tyristors supplying system [fundamental frequency of 50 Hz and harmonics] and (**b**) spatial distribution in front of dielectric heater

over- or under-estimation of the exposure. The results of *Step A* allow selection of EMF assessment criteria, measurements protocol and measurements device in harmony with the characteristic of assessing EMF.

4.2 *Step B*—selection of EMF assessment criteria

The main types of the exposure assessment criteria for various purposes (*Step B*) can be:

– mandatory legislations, voluntary standardizations or guidelines for general public, workers or medical patients EMF exposure assessment,
– mandatory legislations, voluntary standardizations or guidelines for assessing the EMF emission from electrical appliances or environmental EMF exposure assessment, which can play the subsidiary role only,
– EMF exposure assessment guidelines for scientific research (e.g., epidemiological studies).

Usually frequency- and/or time-dependent exposure assessment criteria should be considered when workers exposure is assessing.

4.3 *Step C*—selection of measurements protocol

EMF of a non-uniform spatial distribution can be spatially averaged over human body volume or assessed following maximum spot measurement result found in the workplace (PN-T-06580 2002). For instance values of external measures were calculated to protect against the thermal effect in the body exposed to electric field of the frequencies above 100 kHz and such fields from the workplace should be spatially averaged for the analysis of the compliance with the internal measures' limitations. Time-averaging is always used, e.g., 6-min averaging of *E* and *H* fields from the frequency range 100 kHz–10 GHz, adopted by international recommendations (ICNIRP 1998; IEEE 2004) based on above mentioned thermal effect.

Currently, there is a lack of European exposure standards harmonized with directive 2004/40/EC. Protocols from existing product standards concerning the analysis of compliance with ICNIRP's guidelines for general public exposure assessment, obligatory for laboratory testing of EMF emission from electrical appliances before put it on the European market (emission product standard), can be considered also for the use in real work environment and for the analysis of compliance with the directive's provisions. The method of spatial averaging of the results of measurements of EMF is presented in the European and international standards (EN 50357 2001; and IEC 62369-1 2004) for testing the compliance with exposure limitations published by ICNIRP for general public. Following the provisions of these standards, the torso is the most appropriate part of the body to be considered during assessment and the grid of spot measurement's locations should be used (Fig. 2). The position of the grid in relation to the EMF source under test can vary according to the typical usage of this device, e.g., the height *Z* should be modified for the assessment of a sitting person exposure. The layout and dimensions of the grid shall remain identical.

It should be noticed, that the number of measurements required by such procedure is not acceptable for the practical exposure assessment in the work place and not cover the realistic volume of workers activity (typically at least 1.5 × 1.5 m).

According to IEEE Standard (IEEE 2002), for the measurement of electric or magnetic fields, carried out for the assessment of the whole-body exposure, spatial averaging of the measurement's results means the root mean square of the field over an area equivalent to the vertical

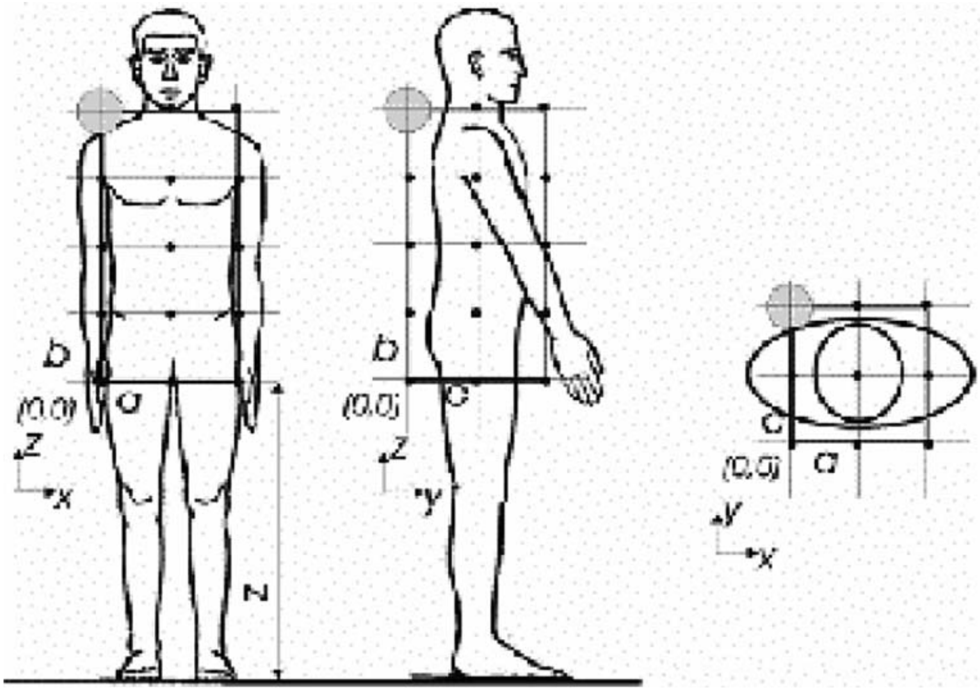

Fig. 2 The grid of spot measurement's locations fixed by product standard EN 50357 for the procedure of assessment of EMF emission form electrical appliances—measurements in 45 locations covering the 0.3 × 0.3 m cross section of the torso of exposed person location

cross section of the adult human body. The spatial average can be measured by scanning (with a suitable measurement probe) a planar area equivalent to the area occupied by a standing adult human (projected area). In the majority of cases, a simple vertical, linear scan of the fields over a 2 m height through the centre of the projected area will be sufficient. IEEE document doesn't describe details how to do spatial averaging.

It should be noticed that the variability of the results of spatial averaging protocol for realistic field distribution in the workplace (e.g., in front of dielectric heater) can be of an order of 3-fold in comparison with maximum value (Gryz et al. 2006) and should be fixed by standardized procedure to obtained the repeatability of measurements results carried by various laboratories. Spatial averaging protocol should be also harmonized with the method of modelling used for deriving the values of external measures limitation from the internal measures limitations.

4.4 *Step D*—selection of measurements device

EMFs are usually measured with handheld devices equipped with various sensors: dipole antennas (for an *E* field), loop antennas (for time-varying *B* and *H* fields or high frequency *E* fields) or Hall-probes (for static magnetic or low-frequency *B*-fields). Power density, *S*, in a far field area can be calculated from the results of *E* field measurements. In the near field area, *E* and *H* components have to be measured independently. A shielded loop antenna is required for measurements of a high frequency *H* field. Broad-band RMS meters as well as a selective one can be used, depending on the frequency composition of measured fields. EMF sensors can be also used with spectrum analysers. EMF meters can be equipped with flat-response wide band antennas or so-called shaped response antennas of frequency respond fitted to the frequency characteristics of permissible electric or magnetic field strength levels. In the case of EMFs composed of components of various frequencies, a shaped response antenna or frequency analysis of a measured field is required to allow estimation of the so-called exposure factor. The definitions of exposure factors depend on the frequency range of EMF.

For the practical EMF exposure assessment at workplace, first of all it should be discussed when it is acceptable to make the EMF exposure assessment by spot measurements with a broad-band RMS meter (i.e., the most convenient and less expensive method). For the other situations, it should be decided the use of more complex (and more expensive) exposure assessment protocol: more detailed measurements or dosimetrical calculations.

4.5 Step *E* and *F*—measurements execution and analysis of the results of measurements

Execution of measurements (*Step E*) and analysis of the obtained results (*Step F*)—e.g., spatial and time averaging of EMF affecting human body or modification of the measurements results with the use of correction factors taking into consideration pulse modulation of assessing EMF—should result in a value of the EMF level parameter selected before for the assessment (e.g., spatially averaged RMS value of magnetic field in selected volume of workplace) and the estimated uncertainty for this value. All steps of the EMF assessment (*Step A–F*) influence on the total uncertainty of knowledge concerning the EMF-level parameter.

4.6 Step *G*—interpretation on the EMF level of exposure conditions under assessment

The interpretation of the obtained results (*Step G*) should be focused on the following questions concerning the EMF level—if the field under assessment is:

– of too high level and reduction action and/or more detailed exposure assessment should be initiated, in the case of human body exposure usually it should be started immediately,
– of high level but from acceptable range and reduction action can be initiated, but not necessary and even human body exposure can be reduce later,
– of low level and it is no needs for reduction action.

All cases of EMF assessment can include the decision process considering the uncertainty and can need decision concerning the uncertainty analysis model, e.g., so-called ‘‘shared uncertainty’’ model of decision. The strongest demands for the uncertainty analysis come from the mandatory legislations of the ‘‘threshold type’’. In such case, if the EMF assessment result is exceeding the EMF threshold (fixed by legislation) this will automatically lead to serious consequences as e.g., financial punishments or obligation to switch-off the EMF emitting devices. For such legislative model of EMF assessment protocol, there is a very strong need for detailed analysis of assessment uncertainty and also for the arbitrary decision concerning the maximum acceptable uncertainty and selection of decision model (e.g., shared uncertainty). On the contrary—the lowest requirements for the uncertainty analysis come from the ‘‘continuous quality improvement type’’ of legislations, standards or guidelines. In such case, the EMF assessment results should always be analysed with consideration the possibility for EMF reduction, but this reduction should be stronger and should be initiated sooner, when the EMF level is higher. In such model, the level of uncertainty can be accepted even of very high value and not calculated in details. The only important requirements are: it can be guaranteed that EMF identification, selection of the assessment criteria, measurement device and measurement protocol were executed properly and harmonized.

4.7 Step *H*—decision on the need for further action

Interpretation of the exposure measurements and assessment can result in the identification of the needs for exposure reduction and/or further more detailed assessment. Such detailed exposure assessment can be executed with the use of numerical modeling of EMF in the workplace and worker’s exposure conditions.

5 Numerical methods for computer-aided electromagnetic hazards assessment

Numerical methods can be successfully used for calculating the parameters of exposure effects in workers body, fixed as the set of internal measures of exposure. These quantities can be calculated using computational methods and anatomically and electrically realistic models of the body, which have a high degree of anatomical resolution (ICNIRP 1998; IEEE 2005).

Because of the electrical inhomogeneity of the body, current densities should be calculated as averages over a cross-section of 1 cm^2 perpendicular to the current direction. Localized SAR averaging mass is any 10 g of contiguous tissue. These 10 g of tissue are intended to be a mass of contiguous tissue with nearly homogeneous electrical properties. A simple geometry such as cubic tissue mass can be used, provided that the calculated dosimetric quantities will be taken as conservative values while its comparison with the exposure guidelines. The following numerical methods are most common: FDTD (finite difference time domain) and FEM (finite element method). Current international standardization work do not covers sufficiently the practical problems existing while workers exposure modelling. The analysis of detailed data obtained from various work place and experience with the numerical calculations modelling realistic exposure scenarios for the assessment of the exposure following the internal measures’ limitations have shown a number of practical problems, identified for the worker’s exposure assessment.

In the most of cases of high-level exposure of workers to LF or IF EMF, their professional activities need hand operation of the EMF sources. For the exposure assessment of such cases the modelling of realistic posture of worker’s body and possible simplifications of it to reduce the complication and costs of exposure assessment process is of high priority (Fig. 3). Important question is on the exposure assessment of hands, especially while hand-operating of EMF sources of high level. The use of calculations for exposure assessment in LF and IF band is more difficult, that RF (with huge experience obtained from mobile phones research) because of:

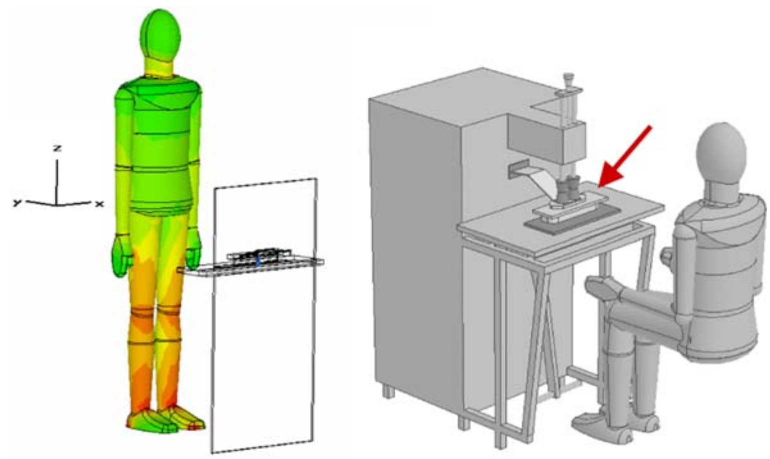

Fig. 3 Examples of workers body modelling for EMF exposure assessment (CIOP-MAN worker's model)

– the lack of models, transferable from one software to other one, representing realistic EMF occupational sources, already verified by reference data from workplaces and taken as standardized models,
– the lack of well verified data on electrical properties of various elements of workplace, as shoes, floor cover, furniture's, etc.,
– relatively small number of the scientific data concerning human body models, electrical properties of tissues, numerical calculations procedures, etc. for the assessment of IF fields.

For the wider use of numerical calculations for the assessment of workers EMF exposure, it is of high priority to obtained well verified scientific data concerning:

– the possibility to use simplified numerical models of working places and EMF exposure conditions,
– the uncertainty of exposure assessment for checking the compliance with the criteria,
– the role of frequency components within the exposure assessment procedures,
– the assessment of pulsed fields, especially in the case of hand-operated devices, when the repetition time of pulses is not fixed.

The practical use of numerical calculations for the EMF exposure assessment is also problematic because it was not defined when various software packages can be use, and none of currently available software is specialized for workers exposure. Additionally, a few commercial human body models are applicable for selected specialized software only. Separate problem is the calculations of induced and contacts currents, which can be also measured.

6 Conclusion

Measurements protocol and measurements devices for occupational EMF exposure assessment against limitations of external measures of exposure should be harmonized with the assessment criteria taken into the consideration. For example, for laboratory testing of EMF emission from large-scale manufacturing electrical appliance (e.g., mobile phone handsets), the measurements protocol can be very detailed and time-consuming because the testing results refer to the huge number of serially produced devices and costs of the testing procedure per each individual appliance will be significantly reduced by their number. At the opposite side of the problem, the protocol for the EMF exposure assessment for the individual workplace should be reasonably simplified to reduce the costs and make the assessment possible in small and medium size enterprises.

The use of internal measures of exposure results for risk evaluation is possible only by simulation computational methods, with the use of adequate representation of the workplace environment and worker's body models. Such calculations for particular exposure situations require highly skilled professionals and specialized software. The modelling of real exposure scenario, validation of calculations results and interpretation of obtained data is usually very time-consuming and currently achievable by research centres only. These are reasons why, the possibility of practical use of numerical modelling by the particular employers, especially from small and medium size enterprises is very limited in contrast to the relatively effective use of such technique for large series manufacturing (e.g., common use electrical devices, like mobile phones handsets). In this respect, the question arises if more simple models are powerful enough for performing roughly assessment of the occupational EMF sources and workers exposure level, while every day's occupational safety and health practice.

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