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Exposure of Workers to Electromagnetic Fields. A Review of Open Questions on Exposure Assessment Techniques

Kjell Hansson Mild

Department of Radiation Sciences, Umeå University, Umeå, Sweden

Tommi Alanko

Finnish Institute of Occupational Health (FIOH), Helsinki, Finland

Gilbert Decat

Flemish Institute of Technological Research (VITO), Mol, Belgium

Rosaria Falsaperla

National Institute of Occupational Safety and Prevention (ISPESL), Rome, Italy

Krzysztof Gryz

Central Institute for Labour Protection – National Research Institute (CIOP-PIB), Poland

Maila Hietanen

Finnish Institute of Occupational Health (FIOH), Helsinki, Finland

Jolanta Karpowicz

Central Institute for Labour Protection – National Research Institute (CIOP-PIB), Poland

Paolo Rossi

National Institute of Occupational Safety and Prevention (ISPESL), Rome, Italy

Monica Sandström

Occupational and Environmental Medicine, Umeå University, Umeå, Sweden

European Directive 2004/40/EC on occupational exposure to electromagnetic fields (EMF), based on the guidelines of the International Commission on Non-Ionizing Radiation Protection, was to be implemented in the Member States of the European Union by 2008. Because of some unexpected problems the deadline was postponed until 2012. This paper reviews some of the problems identified and presents some suggestions for possible solutions based on the authors' experience in assessing occupational exposure to EMF. Among the topics discussed are movement in static magnetic fields, ways to time average extreme low frequency signals, the difference between emission and exposure standards, and ways of dealing with those issues.

occupational exposure exposure assessment measurements numerical simulations safety guidelines EU directive compliance testing medical implants health examination

1. INTRODUCTION

Exposure to strong electromagnetic fields (EMF) can cause harmful health effects. Exposure to a radiofrequency (RF) field of sufficient intensity can cause heating, and the limits and guidelines for human exposure are set to prevent a temperature rise in the body (cf., e.g, International Commission on Non-Ionizing Radiation Protection (ICNIRP) [1] and Institute of Electrical and Electronics Engineers (IEEE) [2]). Intense fields in the extremely low frequency (ELF) range can give rise to significant electric currents in the body and here the exposure limits are set to prevent nerve excitation. For EMF in the intermediate frequency (IF) range both limitations should be considered. For static magnetic fields protection was established against, among others, vertigo and nausea sensations and adverse influence on blood flow [3, 4]. In addition to direct effects of EMF exposure and interaction of the fields with the human body, indirect effects can also be a significant source of hazards related to contact currents, coupling of EMF with medical devices, transient discharges (sparks, which are the basis for safety limits on exposure to static electric fields [1]). Therefore, it is important to have rules and limits for routine control of both general-public and occupational exposure.

High exposure levels, even those exceeding international safety guidelines, can be found for workers operating various kinds of devices that produce EMF [5, 6, Appendix]. Strong exposure to static magnetic fields can be associated with operating a magnetic resonance device (magnetic resonance imaging, MRI, scanners and spectrometers) [7]. A high intensity low frequency magnetic field can be found in the vicinity of welding machines, industrial arc ovens, induction heating furnaces and devices. A high IF magnetic field can also be found near MRI scanners; it is produced by gradient coils and induction heating furnaces devices. A high low frequency electric field can be found in the vicinity of high-voltage power distribution systems. Electrosurgery devices produce an IF electric field. In the RF range workers' exposure near plastic sealers and glue dryers can be substantial. Also radio/TV tower workers are highly exposed. Radar operators can also encounter high-level exposure.

The basic properties of EMF are related to the wavelength and field polarization, characterized by so-called near- or far-field conditions of exposure. EMF in highly exposed work environments are usually near fields. Various physical estimators can be used for assessing EMF exposure at various frequencies:

- internal measures of exposure effects in the body—related to thermal effects (specific energy absorption rate, SAR) or nerve excitation (induced currents, $\boldsymbol{J}$, or in situ electric field, $\boldsymbol{E}_{\text{in}}$);
- external measures of the exposure level of the body—electric field strength ($\boldsymbol{E}$), magnetic field strength ($\boldsymbol{H}$), magnetic flux density ($\boldsymbol{B}$), contact and induced currents flowing through the limbs ($\boldsymbol{I}$), power density ($\boldsymbol{S}$) and surface heating for high frequency.

In a workplace, the geometry and location of the EMF source, as well as the frequency and level of EMF produced by it can be unstable. As a consequence, the characteristics of EMF in the workplace is often more complex and in need of a specific exposure assessment protocol than of fields experienced in a general-public environment. Occupational exposure assessment should always consider the worst-case situation. The most realistic EMF exposure pattern for workers is multifrequency exposure of a variable

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Correspondence and requests for offprints should be sent to Kjell Hansson Mild, Umeå University, Institution of Radiation Sciences, Department of Radiation Physics, S-901 87 Umeå, Sweden. E-mail: <kjell.hansson.mild@radfys.umu.se>. In matters related to offprints or to JOSE, you can also contact the Editorial Office at <jose@ciop.pl>. For more information please see http://www.ciop.pl/jose

level, resulting from nonsinusoidal emission from single or multiple EMF sources, movements of EMF sources, movements of the worker or modulated output power of the EMF source (existing separately or all together). A very complicated exposure assessment protocol is needed when both components, *E* and *H*, should be considered separately as is the case for some workplaces in the vicinity of sources using EMF with frequencies <300 MHz.

Directive 2004/40/EC, the so-called EMF directive, was published in 2004 [8]. Though the limits are based on ICNIRP guidelines [1], there are some important exceptions in the text. The directive was to be implemented in the Member States of the European Union (EU) by 2008. However, because of some unexpected problems with, e.g., exposure near MRI scanners, the deadline was postponed until 2012. The results of various actions related to the implementation of the provisions of the directive bring up new problems and questions related to the legal interpretation of EMF exposure assessment guidelines and protocols. This paper reviews some of those problems. It also presents some suggestions for possible solutions based on these authors' experience in assessing occupational exposure to EMF and related matters.

Though there may exist other classifications of the frequency spectrum, this paper uses the following notation of EMF frequency ranges: static fields—0 Hz; ELF—time-varying fields of the frequency <300 Hz; IF—time-varying fields of the frequency between ELF and RF, with special attention to 100 kHz–10 MHz; and RF—time-varying fields or radiation of frequency >10 MHz

2. STATIC MAGNETIC FIELDS

Directive 2004/40/EC fixes an exposure limit for induced current density of 40 mA/m^2 for exposure to electromagnetic fields of frequency <1 Hz [8]. However, the action level for these frequencies is set by the directive at 200 mT of the magnetic field (the E-field is not covered), but no value is specified separately for static magnetic fields ($f = 0$ Hz). In ICNIRP guidelines [1], chosen as the background for the provisions of the directive, there is a reference to another ICNIRP document [4], which includes exposure limits for static magnetic fields (Table 1), but it is not clear how workers' exposure near, e.g., MRI scanners, should be treated.

Movement in static magnetic fields gives rise to induced currents in the body. The aforementioned limit for induced current can be also seen to cover the results of movement in static magnetic fields. From a biophysical point of view, the current induced in the body when a person is moving in a static magnetic field should be treated in the same way as the current resulting from exposure to a time-varying magnetic field. At the moment it is not clear if this is a case for legal interpretation. For workplace safety during activities in the vicinity of magnets, these currents play an important role since they may cause sensations like vertigo or difficulties in eye–hand co-ordination and balance. In the regular process of updating ICNIRP guidelines [1] and Directive 2004/40/EC [8], a solution to this problem should be clearly defined.

The only references of Directive 2004/40/EC that focus directly on static magnetic fields are the indirect effect on medical implants (without

TABLE 1. Permissible Occupational Exposure to a Static Magnetic Field (mT) [54]

	Whole Body		Limbs		Users With Cardiac Stimulators and Implanted Electronically Activated Devices
Recommending Body	Whole Working Day	Ceiling Value	Whole Working Day	Ceiling Value	
ICNIRP [4]	200	2000	not defined	5000	0.5
European Union [8]	200	not defined	not defined	not defined	mentioned but not defined
IEEE [3]	500	500	500	500	mentioned but not defined
ACGIH [12]	60	2000	600	5000	0.5

Notes. ICNIRP—International Commission on Non-Ionizing Radiation Protection, IEEE—Institute of Electrical and Electronics Engineers, ACGIH—American Conference of Government Industrial Hygienist.

providing limits preventing such effects) and the projectile risk from ferromagnetic objects in a B-field of >3 mT [8]. It would be also important to know if the 0.5 mT B-field (indicated by some documents as the safety limit for persons with medical implants, e.g., pacemakers [4, 9, 10, 11, 12, 13]) is a valid interference level for both old and new generations of pacemakers (PM) and/or other electronic implants. It is also important what advice should be given to current and future users of various generations of implants like PM, defibrillators, infusion pumps (e.g., insulin pumps, dozers), cochlear implants, on continuing or entering activities that involve EMF exposure.

3. ELF MAGNETIC FIELDS

Exposure assessment with respect to occupational exposure to the ELF range of EMF has many unanswered questions, many of which must be first of all addressed by ICNIRP or other guidelines-setting bodies before solutions can be introduced in the revision of Directive 2004/40/EC [8]. This paper presents some problems encountered during occupational exposure assessment in various environments. It also addresses some problems identified in the provisions of the European Committee for Electrotechnical Standardization (CENELEC) standards for measurements [37, 38].

3.1. Time Averaging

Time averaging in ELF exposure should be discussed first. The limits for exposure to ELF fields are set to protect against nerve excitation, which can happen even within a half-period of the power frequency alternating current (AC), i.e., during exposure of <10 ms [14]. However, usually the limits are set in root-mean-square[1] (rms) values for field strengths, and then the same applies to the corresponding time to be used for assessing induced current density.

Should these quantities be averaged over one second or a shorter time period? Various standards give different answers, but since most commercially available instruments use one second as averaging time, this is the most commonly used period. In contrast, Directive 2004/40/EC does not specify any averaging time for frequencies <100 kHz [8].

Standard No. C.95.6:2002 gives the rms averaging time as the longer of 0.2 s or 5 cycles (up to 10 s) [3]. However, even the use of this standard might be problematic. An assessment of exposure produced by a spot welding machine is an example. The total welding time, i.e., time when the current is on, is typically shorter than one second, even only a few periods of 50 Hz (i.e., the order of tens or hundreds of 1 ms) (Figure 1a). The whole weld is over before the averaging time is up. The amount of heat needed and the welding current are regulated with thyristors, which can lead to a high harmonic content in the current and the corresponding magnetic field (Figures 1b, 1c).

An alternative to the rms value assessment approach to exposure assessment is peak value assessment (B or $\mathrm{d}B/\mathrm{d}t$); it omits time averaging altogether (cf. section 3.2.) [21]. Time averaging is also a problem when dealing with handheld tools. Standard No. EN 62233:2008 states that the measurement should be taken at a certain distance from the machine, and the first 200 ms from the start-up the machine should be neglected [16]. The machine usually draws 10 times more current during the first few periods and the corresponding magnetic field is also strongest then (cf. Figure 2 for an illustration of the current drawn during the start-up of an ordinary electric drill).

[1] A root-mean-square (rms) value is an effective value or a value associated with joule heating, of a periodic signal. It is obtained by taking the square root of the mean of the squared value of a function:

$x_{\mathrm{rms}} = \sqrt{\frac{1}{T}\int_0^T x^2(t)\mathrm{d}t}$ (an expression in the time domain), where $x(t)$ is the signal at time t, T is the signal period or multiplies of it;

$x_{\mathrm{rms}} = \sqrt{\sum_n x_n^2}$ (an expression in the frequency domain), where x_{n} is the magnitude of spectral component at n-th frequency, expressed as an rms value [15].

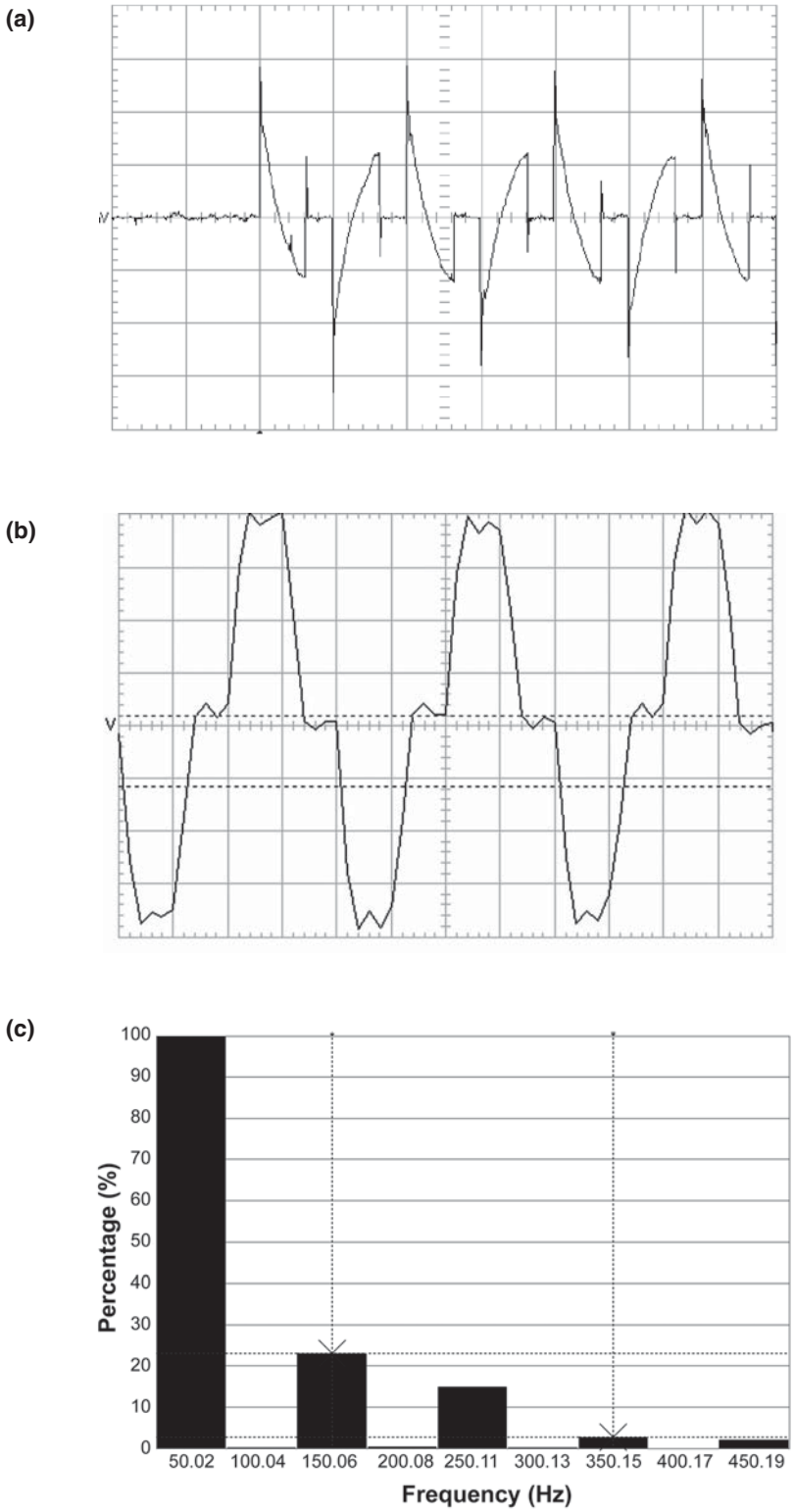

Figure 1. Magnetic field from a spot welding machine: (a) time derivative d*B*/d*t* recorded with a small pick up coil, 10 ms/div; (b) magnetic field recorded with a flat respond probe, 5 ms/div; (c) relative amplitudes of components of the frequency spectrum of the wave from Figure 1b, basic frequency 50 Hz (100%), and following odd harmonics.

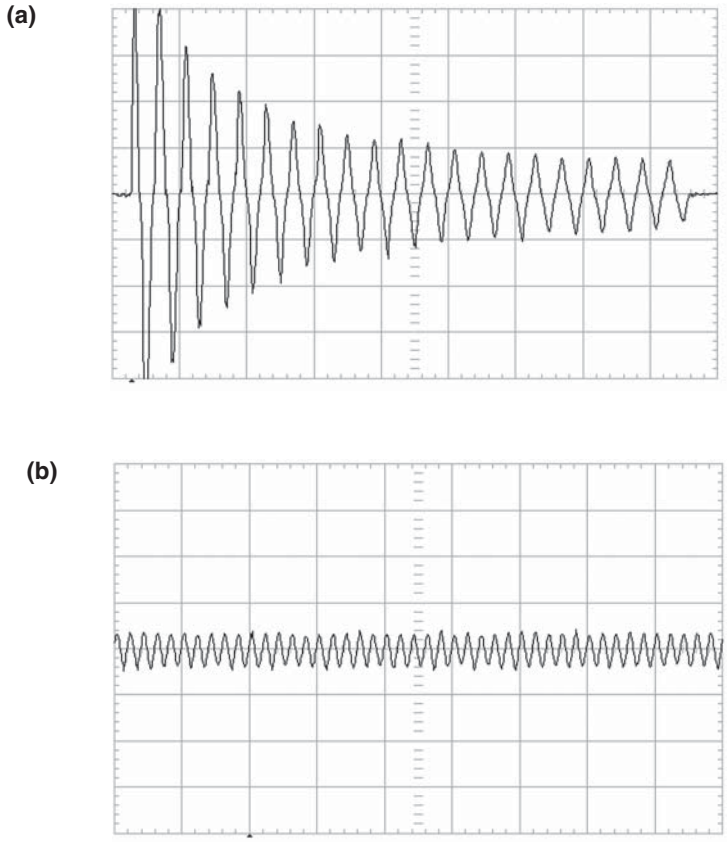

Figure 2. Measurement of the current drawn from the net with an ordinary electric drill during a start-up procedure: time resolution (a) starting phase, 50 ms/div; (b) steady-state phase, 100 ms/div; amplitude resolution, 10 A/V and 0.5 V/div.

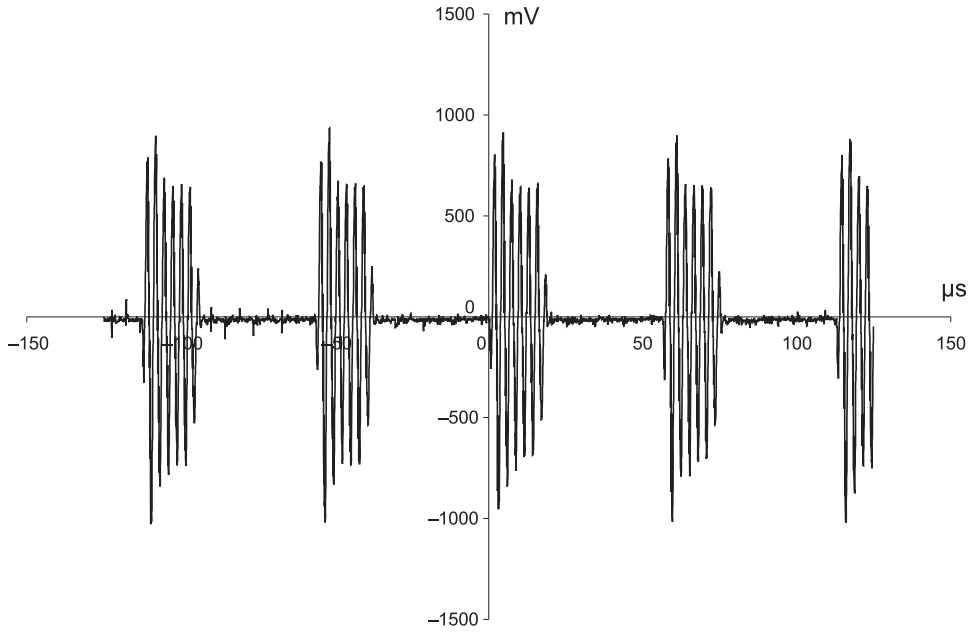

Figure 3. Oscilloscope image of the current in a cable of a surgical diathermy at dry-cut setting. The frequency of the signal is ~500 kHz and the repetition frequency for the pulse is ~20 kHz.

Since the aim of the ICNIRP guidelines [1] and Directive 2004/40/EC [8] is to protect workers from nerve excitation, this exception is in conflict with the biomedical rationale for safety guidance. In this case it is really the first periods that count, especially when applying the principle of the worst-case exposure assessment and taking into account that ICNIRP provides limits for peak values.

A practical technical problem related to the time averaging of the parameters of the EMF exposure level is the integration time of the measurement devices, usually calibrated for measurements of rms values of sinusoidal fields. Typical integration time is of the order of one second; thus, shorter exposures cannot be properly evaluated with such instrumentation and other specific devices are necessary.

Electronic article surveillance (EAS) systems are another area where time averaging is an obvious problem. For instance, library acoustomagnetic systems operate with pulsed signals. Estenberg, Anger and Trulsson [17], Trulsson, Anger and Estenberg [18] and Standard No. EN 50357:2001 [19] give detailed waveform descriptions for different systems. One of the systems uses a frequency of 58 kHz with a pulse length of 2.2 ms and a repetition pulse length of 13.4 ms (typical values for most systems are around these values). From the measured total rms value, an rms value for the pulse is calculated from the duty cycle, and then it is compared with the guidelines. Thus, here the rms is taken over ~2 ms (pulse duration only) and then compared with the standard. However, there is no legal interpretation if Directive 2004/40/EC requires such a protocol for evaluating pulsed fields [8]; perhaps a peak value limitation approach should apply. It is also difficult to find a device capable of performing proper measurements of rms values for such pulsed fields.

Exposure near surgical diathermy apparatus is a similar case. Here the settings for spray/coagulation can use pulsed signals with the frequency of ~500 kHz, from a single period to a few in the pulse depending on the need, and with a repetition frequency of some tens of kilohertz (Figure 3). Should the rms of the total signal be taken or should individual pulses be assessed separately?

Before leaving the time average problem, the lack of specific mentioning in Directive 2004/40/EC [8] of time averaging for contact current also should be brought up.

3.2. Emission Versus Exposure Standards

Another problem to be discussed is the difference between emission and exposure standards. Emission standards are created to provide standardised procedures for laboratory testing of the level of selected parameters of EMF produced by specific types of electrical appliances. Exposure standards, on the other hand, have to apply to the real work environment and the measurement should refer to worst-case exposure scenarios.

The differences among these two approaches can be exemplified with measurements of electrical welding equipment. According to Standard No. EN 50444:2008 measurements should be taken with the probe tip 20 cm from the cable with the use of circular probes with a given diameter [20]. Such a relatively long distance from the EMF source is required for repeatable results of measurements and reduced sensitivity of the results to the diameter and shape of the B-field probe. Simultaneous measurements for the same welding conditions (tungsten inert gas AC aluminium welding) with a circular (100 cm^2) and a squared (80 cm^2) loop antenna probe resulted in different values of magnetic flux densities (Figure 4). The shorter the distance to the cable, the larger the discrepancy between the results from the two probes. It is also possible to use a Hall-sensor probe for such measurements. As a Hall probe is <1 cm, those discrepancies can be much higher.

In the worst-case exposure scenario the distance between the worker's body and the cable is <20 cm. The cable usually is in direct contact with the body regardless of its part; it may even be over the heart, along the spinal cord, testes, etc. The B-field strength with the probe tip on the cable might be threefold higher or more, than that obtained 20 cm from it. Therefore, an assessment of occupational exposure during welding must

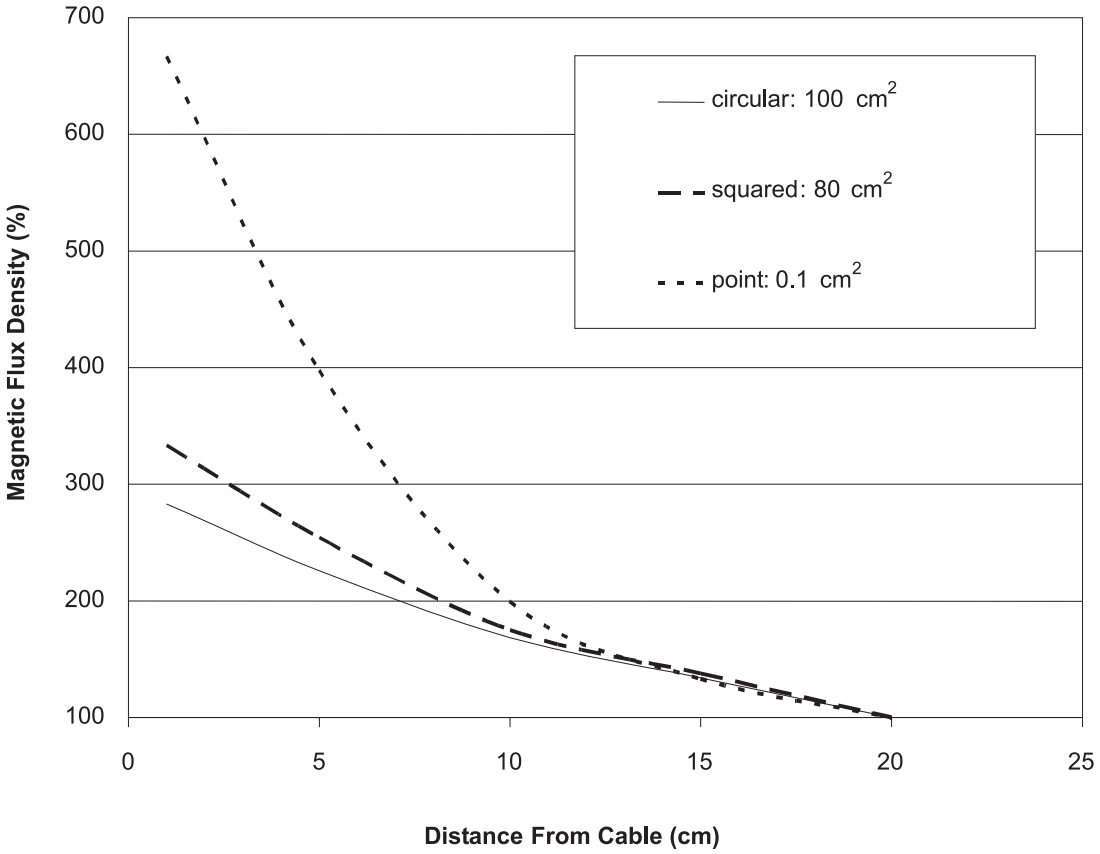

Figure 4. B-field near a welding cable measured with various types of probes: circular (100 cm^2), squared (80 cm^2) and point (0.1 cm^2), distance between the surface of the cable and tip of the probes, relative level of magnetic field, 100% is the field measured at the distance of 20 cm.

take as a starting point how the welder is holding the cable, and not be limited to a fixed distance of 20 cm.

Measurements with the probe directly on the cable are highly imprecise, because the results are very sensitive to the location of the probe. Such use of the device can be related with the possible coupling of the sensor with the EMF source, and is very different from that used in calibrating the device. A possible solution is to work out an interpretation of the results of standardised measurements (e.g., 20 cm from the cable) with the use of a compensation factor (i.e., multiplication by some number before a comparison with a limit value). The compensation factor could represent how much higher a realistic exposure of the worker is in comparison with the field assessed during an emission testing procedure. The problem is how the compensation factor can be defined correctly.

Another approach would be to measure the current in the welding cable with a clamp-on current meter. Such measurements could then be used in calculating the magnetic field at the desired position. The harmonic content of the current and the corresponding magnetic field can also be obtained from a measurement of the current.

Some open questions regarding handheld tools have to be discussed. According to Standard No. EN 62233:2008 the measurement on handheld tools should be taken at a certain distance from the machine [16]. The frequency summation of the harmonics (exposure factor *W*), which the ICNIRP guidelines [1] give as a linear summation of frequency components for frequencies under 10 MHz taking into account that the limits are lower at higher frequencies (Equation 1). However, Standard No. EN 62233:2008 defines summation as summation of the square of the ratios (Equation 2). Thus, Equation 2 significantly holds back the influence of the higher harmonics on the summation result (e.g., for harmonics of the power frequency signal). This is not in line

with the protection aimed at in ICNIRP [1] and declared in Directive 2004/40/EC [8]:

$$\sum_{j=1\text{Hz}}^{65\text{kHz}} \frac{H_j}{H_{\text{L},j}} + \sum_{j>65\text{kHz}}^{10\text{MHz}} \frac{H_j}{b} \le 1 \quad [1], \qquad (1)$$

$$W_n = \sqrt{\sum_{j=1}^{n} \left(\frac{B(j)}{B_{\text{RL}}(j)} \right)^2} \quad [16]. \qquad (2)$$

For example, for a complex field composed of two frequencies, 50 Hz, of the level of 50 μT (i.e., 10% of the exposure level permissible for workers' exposure) and 300 Hz of the level of 10 μT (i.e., 12% of the exposure level permissible for workers' exposure) Equation 1 (the ICNIRP-based exposure factor) yields an exposure factor of 22% of workers' permissible exposure, whereas Equation 2 (the CENELEC-based exposure factor) yields only 15.6% of workers' permissible exposure. Such a practice applied to weak fields, which are typical for general-public exposure, could be acceptable but it does not seem to be in agreement with the provisions of Directive 2004/40/EC for high-level exposure of workers [8].

Standardised protocols for testing emission levels can be very precise and can take up substantial working time and resources. Such procedures will provide data for comparing parameters of selected devices, and the main role in drafting such documents is played by representatives of the industry involved in the manufacturing of the devices. A researcher can seldom afford to participate. Exposure assessment standards, on the other hand, should cover every scenario of workers' exposure to EMF, including worst-case exposure, e.g., when a device with removed safety locks is repaired. Standardised protocols for exposure assessment should be created in such a way that assessment can be done in every workplace with limited resources for testing measurements and limited access time to the workplace. Independent experts experienced in occupational EMF assessment, representatives of the trade unions and regulatory bodies should draft such documents to ensure harmonisation of the standard with the requirements of legislation on workers' exposure limitations and coverage of realistic exposure scenarios. It is very difficult to fulfil such requirements within the current structure of CENELEC working groups, so perhaps requirements essential for exposure assessment should be included in the revised directive on EMF limitation in the workplace.

4. NONSINUSOIDAL AND PULSED FIELDS

Most exposure in the ELF range is nonsinusoidal and this problem has been dealt in an ICNIRP publication [21]. Instead of doing Fourier analyses of the signal and frequency summation—with or without taking the phase into account—it is suggested that it is sufficient to measure the peak value, which can be expressed in B or $\mathrm{d}B/\mathrm{d}t$ (time derivative of the B-field). However, when the peak approach (e.g., a weighted peak) is used, only the level of the peak is considered; the remaining parts of the signal are of no interest. However, when the rms approach is used, the peak value is the most important part of the results of the measurements with a slight contribution from the remaining components of the signal (the rms value is slightly higher than if only the peak is taken into account).

In contrast, when the exposure factor approach is used, the peak value can be less important for the results of exposure assessment because of a possible important contribution from components of higher frequencies. The value of the exposure factor can be much greater than if only the peak is taken into account (cf. section 3). This can be also exemplified with the short-arc welding sequence in Figure 5, where the peak only picks up the first part of the signal and the rest is neglected. In contrast, the exposure factor and rms take into account higher harmonics and the shape of the signal between peaks, too.

The problem is the same when exposure to the magnetic field from MRI equipment and $\mathrm{d}B/\mathrm{d}t$ are considered: the weighted peak $\mathrm{d}B/\mathrm{d}t$ approach is an option for assessing pulsed fields [21]. In this approach there is really no time averaging given, but from the duration of the pulse a corresponding frequency can be calculated to give the value of the allowed induced current

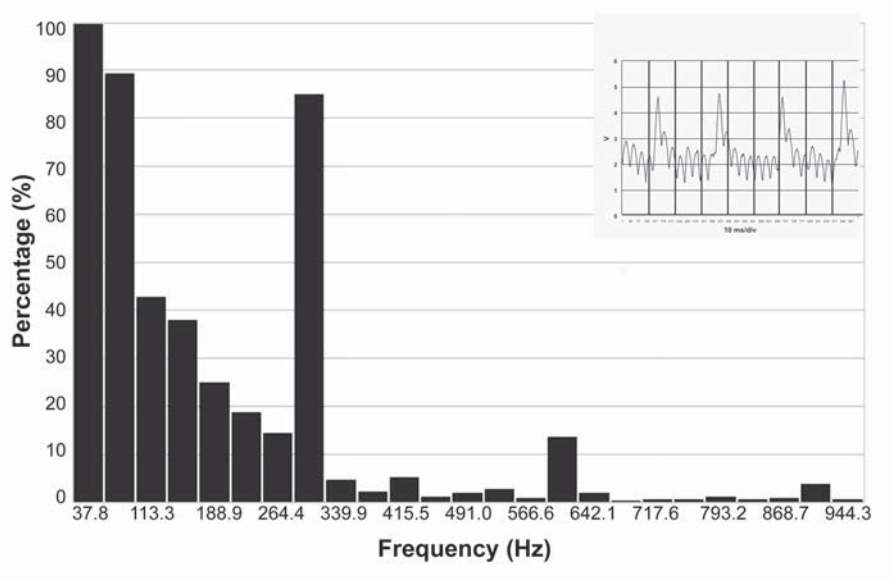

Figure 5. An example of a recording of the welding current and the corresponding fast Fourier transform (FFT) analyses from a short-arc weld.

[21, 23, 24]. Standard No. IEC 601-2-33:1995 [9], in 2002 accepted as Standard No. EN 60601-2-33:2002 [10], presents a somewhat different approach to d*B*/d*t* assessment [22]. The question is if the pulse sequence with a single pulse repeated very slowly should be regarded as the same as a more rapid pulse sequence, assuming equal amplitude and rise time. Standards No. IEC-601-2-33:1995 and No. EN 60601-2-33:2002 established a maximum level of d*B*/d*t* for pulses >0.12 ms (for patients undergoing MRI examinations) and higher permissible exposure for shorter pulses. The permissible value of d*B*/d*t* rises to its maximum for pulses ≤0.0025 ms. For repetitive waves, pulse duration is a half-period of the wave. The IEC limitation is based on the thermal effects from sinusoidal wave exposure. Further relaxation of the permissible level of d*B*/d*t* is provided for nonsinusoidal pulses. Directive 2004/40/EC [8], based on the ICNIRP guidelines [1, 21], adopted a different approach for the d*B*/d*t* assessment (based on the peripheral nerve excitation mechanism) than Standard No. EN 60601-2-33:2002 [10]. The legislative question is which one should have priority in occupational safety and health (OSH) practice.

An interpretation is also needed for the ICNIRP approach, which was presented on the basis of the model of excitation mechanism for peripheral nerves [21]. That model was based on Jokela's calculations on the spatially extended nonlinear node model for a myelinated axon [23]. In contrast, the provisions of Directive 2004/40/EC are set to protect against central nervous system excitation [8]. However, the directive also refers to ICNIRP's recommendation on assessing the d*B*/d*t* parameter for magnetic fields. Presumably, the limitation of available knowledge about nerve physiology, which would allow us to decide how to consider a single pulse versus repeated pulses, is the problem (Figure 6).

When using fast Fourier transform (FFT) analyses for transients and continuous signals, different approaches should be used. FFT assumes that the analysed sample is repeated infinitely, and that the beginning and the end of the sample fit together seamlessly. In the case of a continuous signal, this corresponds quite well to the actual situation. The periodic signal can be represented by one period but usually in these cases the frequency resolution FFT solvers provide is poor. However, a numerical application that solves such cases can be found. By including several periods into the analysed signal (several samples) the frequency resolution of the obtained FFT spectrum increases as the sample number increases. The effect is demonstrated in Figure 7, in which three different numbers of periods of

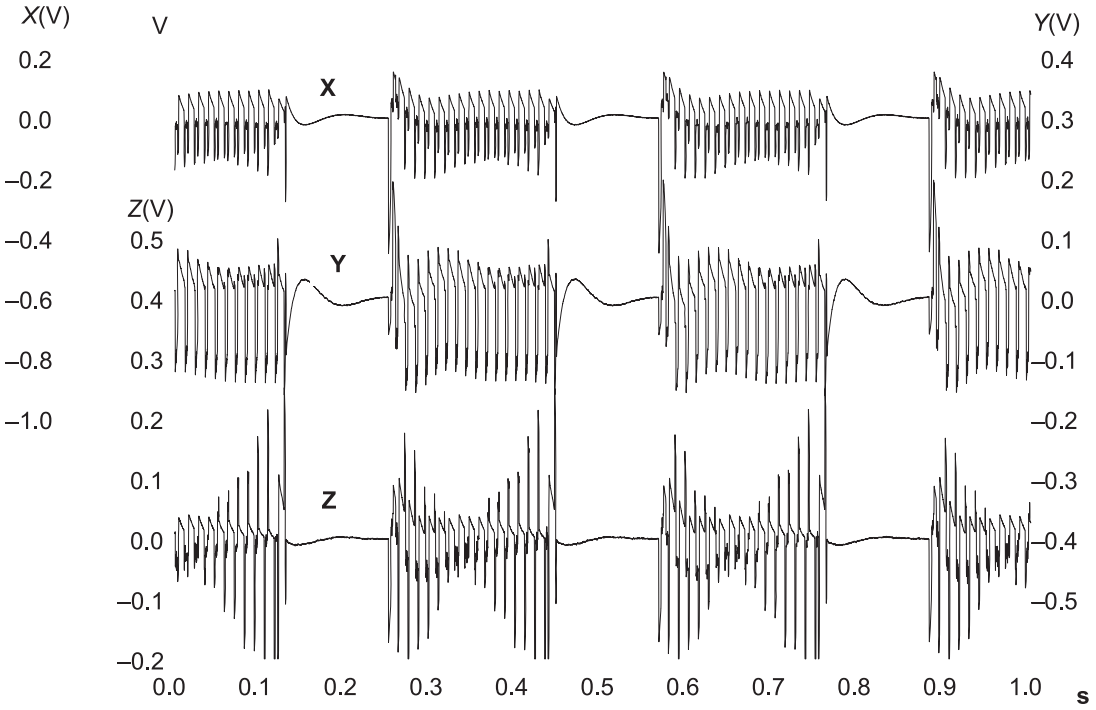

Figure 6. Measurement of dB/dt in front of a 1.5 T MRI scanner running a T2 spin-echo pulse sequence. *Notes.* MRI—magnetic resonance imaging.

the sine wave are analysed with the FFT solver (MATLAB software from MathWorks).

Windowing in an important property of the numerical protocol, which affects the results of FFT. It is used to smooth the edges of time recording. For periodic signals sampling may lead to a discontinuity, which in FFT leads to the smearing of energy throughout the frequency domain (Figure 8). Windowing reduces the significance of the edges of the time record (Figures 8a, 8b). It is important to understand that the use of windowing in the case of a transient event will distort the frequency information as transient strength decreases at the beginning where it would otherwise be strongest (Figures 8c, 8d). In many analysers windowing is used as a default setting, which may lead to unwanted results. There are also several different windowing functions, all of which are used in specific circumstances. The use of FFT in exposure assessment is demanding, and the user should know all the demands and limitations of the method for different waveforms and situations.

When dealing with FFT analyses, the following questions need to be considered. How does this method compare with the dB/dt approach? How many periods should be used in the analyses: is one period enough or do we need 10 or more? How should we deal with signals whose shape varies from one period to the next (which is typical for industrial high power appliances)? How should periods be selected? What numerical procedure should be used in FFT analysis? The Hanning window, perhaps? Should we use the worst-case approach without considering the phases of the frequency components, or exposure assessment with attention to the phases of the frequency components and their effect on the result? A study to clarify this should be performed and perhaps a new approach, better harmonised with the nature of the signal and its biological effectiveness, should be worked out.

Legislation, such as a directive, should define a reference method. Then standardised procedures should provide details for practical assessment of particular types of time-variability of exposure.

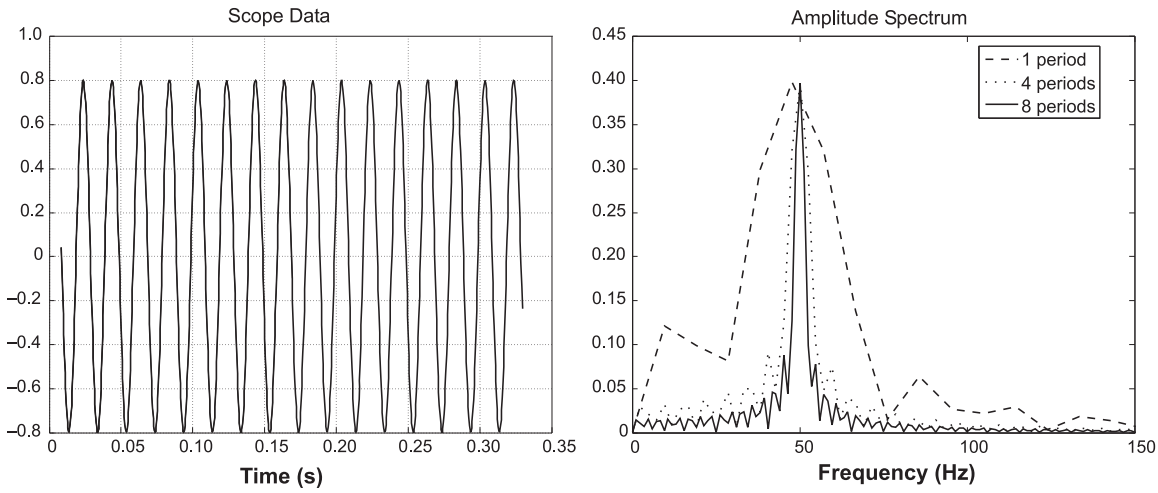

Figure 7. The effect of the number of periods on the frequency resolution with the constant time domain sampling rate (an example of calculation results from a fast Fourier transform (FFT) solver; MATLAB software from MathWorks).

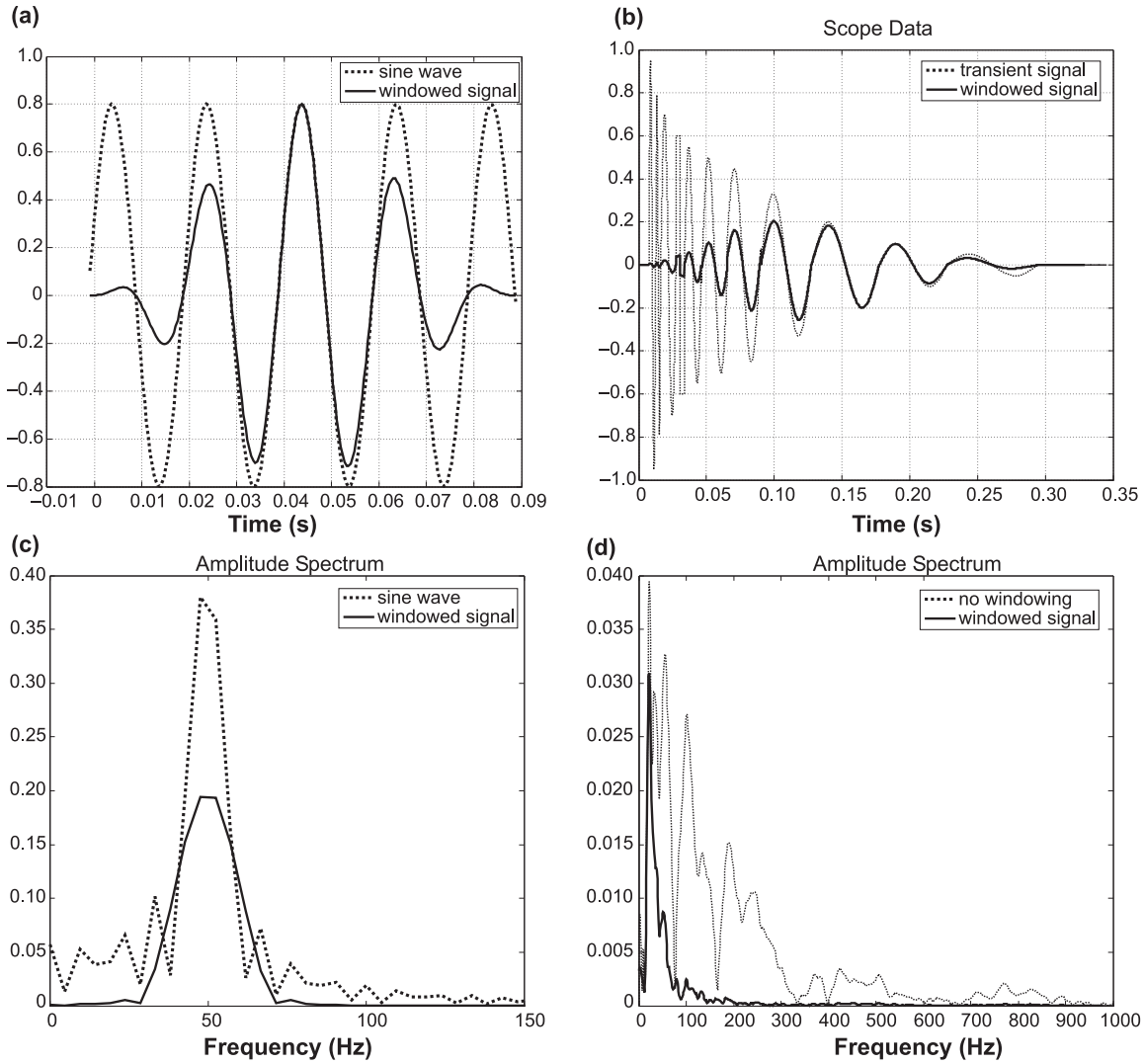

Figure 8. (a) Sine wave and corresponding Hanning windowed wave, (b) fast Fourier transform (FFT) results from waveforms of Figure 7a, (c) transient signal and corresponding Hanning windowed wave, (d) FFT results from waveforms of Figure 7c.

5. ELF ELECTRIC FIELDS

One of the problems with the requirements of Directive 2004/40/EC for power frequency electric fields is that it now gives 10 kV/m as the highest value for working in a 50-Hz environment [8]. However, the ICNIRP guidelines make increasing this by a factor of 2 possible, if the worker is not in contact with electrical grounds [1]. This is so, because the limit is based on avoiding spark discharges rather than on an induced current density limit. Work in existing high-voltage switchyards, of which there are many hundreds of thousands all over Europe, may be problematic with the low 10 kV/m limit. Numerical modelling of exposure conditions in each switchyard to test compliance with the Directive 2004/40/EC limits for induced currents density seems impossible. This is so both due to the time and budget needed for such work, and to the fact that this limit for the E-field is based on avoiding spark discharges and not current density in the body. If work can be done without coming in contact with electrical ground this exception could be provided by responsible decision-makers at the European or national level. This example shows how detailed the interpretation of the provisions of a directive must be and how precision of legislation can significantly reduce its financial consequences.

When assessing the electric field, it is very important that the measurements be done in an unperturbed field and not with workers or other bystanders too close. The latter would give large errors because of the modification of the spatial distribution of the assessed field. There are only a few types of commercial instruments for measuring an unperturbed ELF electric field (e.g., ones equipped with fiber optic or ultrasound separation of the E-field sensor and the monitor of the instrument).

6. IF FIELDS

Significant occupational exposure to EMF in the IF range is caused by induction heaters (operating usually from 1 kHz to low MHz), welding devices (common sources of ELF EMF but also possible source of tens of hundreds kHz), electrosurgery units (usually sources of 300 kHz–1.5 MHz), antitheft devices, etc.

Exposure assessment of IF EMF requires the use of almost all EMF exposure estimators: SAR, induced currents, in situ electric field, electric field strength (E), magnetic field strength (H), magnetic flux density (B), contact and induced currents flowing through the limbs (I) [25]. The technical and interpretation problems identified for EMF of this frequency also exist in lower and higher frequency ranges; they are discussed in detail in other sections of this paper.

Lack of well-established biomedical rationale for exposure limitation in that range is the greatest problem in assessing the level of hazards caused by IF EMF exposure; scientific background exists mostly for power frequency and RF exposures.

7. RF FIELDS

Ways of determining the worst case of exposure for a particular working situation are one of the first problems to be dealt with when assessing exposure to RF fields. It is not always possible to cover all situations during one measurement session. However, it is as necessary to ensure that exposure is assessed as to take into account the worst-case scenario. When assessing an RF plastic sealer (also called a dielectric heater), the type of plastic being welded, the number of layers of plastic and the length of the electrode are all important since they influence the leakage fields from the machine. Before an EMF is measured, it is necessary to test if the plastic the workers use produces the worst case; different plastic materials have different dielectric properties and thus require different intensities of RF to produce a good weld. Moreover, the electrode temperature affects the level of voltage to be applied to the electrode and the level of exposure in the vicinity of the device. A standardised protocol for such measurements should provide practical advice on these technical problems.

For RF plastic sealers it is necessary to measure all parameters given in the directive: E- and H-fields, and contact and induced current. The fields can be quite strong near the electrode; the electrode voltage to ground can be >2 kV. Spatial

distribution is usually heterogeneous in front of electrodes (Figure 9). It is not usually a question if actions levels are exceeded or not, but rather how close one can come to the machine before they are exceeded.

Extensive measurements often have to be taken with spatial averaging over the body. The measurement protocol can require selecting 4–6 spots, e.g., at the head, chest, groin and thighs, and performing measurements of unperturbed E- and H-fields, i.e., without the operator present. This is so because the fields are strongly distorted by the presence a person. The spatial averaging has to be done on the E^2 or H^2 values, since the exposure limit is based on SAR, which is directly proportional to these values. There is an error in the corrigendum to the directive, where it is wrongly said that both the time average and the spatial average should be done linearly [26]. The difference between the linear or squared approaches can be rather large. Wilén, Hörnsten, Sandström, et al. [27] measured exposure in front of RF sealers and reported averaged spatial values calculated both as linear and squared mean values of the exposure over the entire body (e.g., measured values close to the head, chest, wrist, hands, knees and feet) and according to ICNIRP [1] as a 6-min time averaged and spatial average of E^2 and H^2 values. The difference could be up to 30% with the linear always lower.

European exposure standards and drafts harmonised with Directive 2004/40/EC are not precise on the spatial averaging of spatially heterogeneous fields in the workplace [8]. Protocols from existing product standards on analysing compliance with ICNIRP guidelines for general-public exposure assessment, obligatory for laboratory testing of EMF emission from electrical appliances before entering the European market (the emission product standard [39, 40, 44]) can be also considered an example of a possible solution on how spatial averaging in a real work environment can be performed in an analysis of compliance with the provisions of the directive. European and international standards on antitheft gates describe the method of spatial averaging of the results of measurements of series of spot measurements of EMF [19, 28].

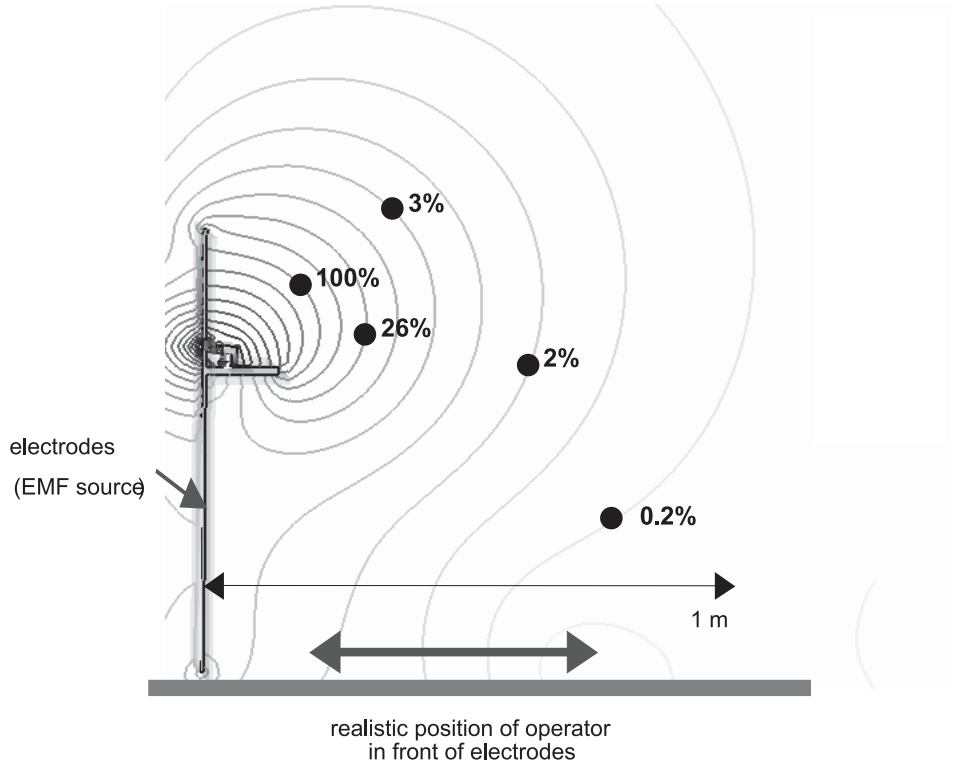

Figure 9. Examples of spatial distribution of electric field strength in front of a plastic sealer; the height of the electrode: 80 cm [7]. *Notes.* EMF—electromagnetic fields.

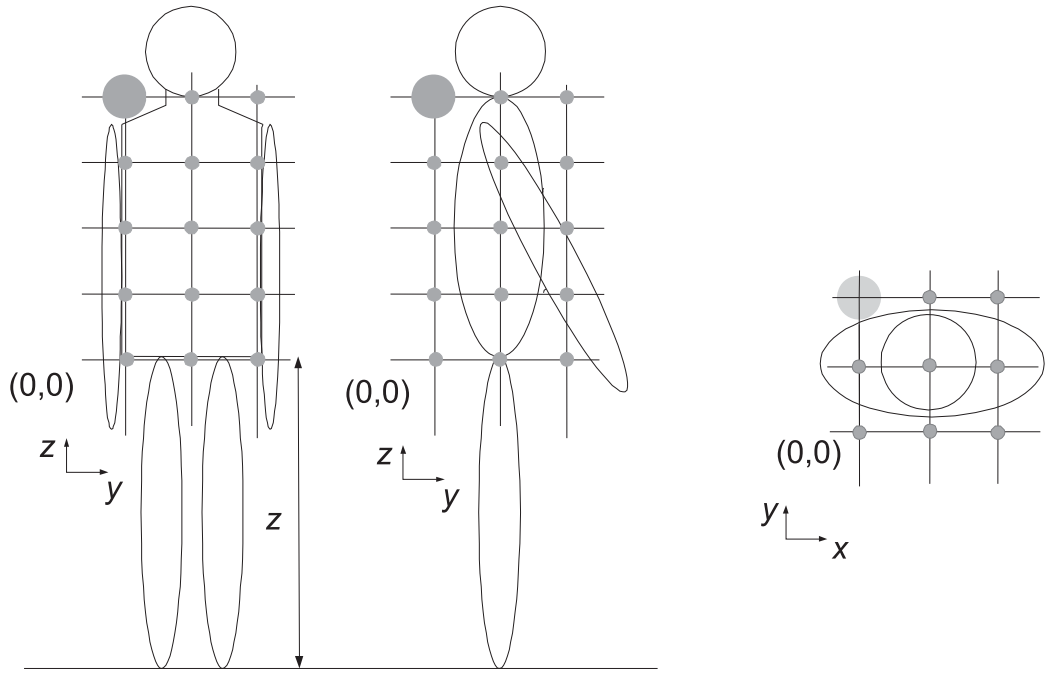

Figure 10. The grid of the locations of spot measurements fixed by Standard No. EN 50357:2001 [19] for the procedure of assessing EMF emission from electrical appliances; measurements in 45 locations covering the 0.3 × 0.3 m cross-section of the torso of the exposed person. *Notes.* EMF—electromagnetic fields.

According to these standards, the torso is the most suitable part of the body to assess and a grid of the locations of spot measurements should be used (Figure 10). The position of the grid in relation to the EMF source tested can vary according to the typical use of this device, e.g., the height *Z* should be modified when exposure of a sitting person is assessed. The layout and dimensions of the grid should remain identical.

The number of measurements required by such a procedure is very high (there are 45 locations) and rather not practical, especially when the grid is extended to the typical volume of the space of a worker's activity in front of an operated device (typically at least 1.5 × 1.5 m).

Another example of the spatial averaging protocol can be taken from Standard No. C.95.1:2005 [2]. For measurements of electric or magnetic fields carried out for the assessment of whole-body exposure, spatial averaging of the results means the rms of the field over an area equivalent to the vertical 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 (a projected area). In most cases, a simple vertical, linear scan of the fields over a 2-m height through the centre of the projected area is sufficient. Standard No. C.95.1:2005 does not describe details on how spatial averaging should be done.

Gryz, Karpowicz, Molenda et al. analysed the results of spot measurements of spatial distribution of an E-field (with spatial resolution similar to that in the protocol established by Standard No. EN 50357:2001 [19]) in front of four dielectric heaters, and numerical simulations of E-field distribution in the vicinity of models of those dielectric heaters [29]. They used software for finite element methods (Opera 3d version 8.5, from Vector Fields) and for finite integration techniques (CST Microwave Studio® version 2006, from CST). The results of using various protocols for spatial averaging (Standards No. EN 50357:2001 and No. C.95.1:2005 [2]) show that the value of a spatial averaged E-field varies in the range of 30–90% of the maximum value over the vertical axis of the trunk of a worker operating devices (representing the level of the worker's exposure following the requirements

from Standard No. PN-T-06580:2002 [22, 30]). The decision-makers responsible for setting exposure limits and definitions of the parameters of exposure should consider such substantial variability.

If the spatially averaged value is below the action level, then the requirements of Directive 2004/40/EC are met [8]. If not, time averaging is the next step. Then, the duration of exposure and the process duty cycle should be evaluated. This should then be applied to the spatially averaged value to see how it compares with the action levels. Since the SAR limit has to be time averaged over any 6-min period (originally expressed as 0.1 h) the time averaging has to be done on the squared value of the field. If it is still in excess of the limit values, further actions are needed to reduce exposure, or numerical calculations can be performed to show compliance with the basic restrictions.

However, spatial averaging is not problem-free since the ICNIRP guidelines state "The reference levels are intended to be spatially averaged values over the entire body of the exposed individual, but with the important proviso that the basic restrictions on localized exposure are not exceeded" (p. 509) [1]. Yet, how can this be shown without extensive numerical calculations? To be on the safe side in the worst case of heterogeneous spatial distribution of exposure, no spatial averaging should be performed. For practical use, well-documented data on the parameters of localised exposure from typical EMF sources and distribution of localised SAR should be published under the auspices of authorities.

For the RF range it is also necessary to measure both induced and contact currents. This should then be combined with measurements of E- and H-fields according to ICNIRP guidelines [1]. In the numerical calculations everything should be taken into account; it is questionable if many experts are capable of such calculations in a realistic case, taking into account the time and resources such a project would consume. It is, therefore, most likely that the action levels become the in facto conclusive limits instead.

Another problem that has to be dealt with in RF assessment is how to deal with exposure when the heating process is a gradually increasing one (e.g., in induction ovens) associated with proportionally (step-by-step) increasing power for melting plastic. Is the time integrated field averaged over the whole process cycle the determining factor for an effect or is it the peak or the time averaged value over the final step of the process, e.g., when operating melting temperature is reached? The worst case is, of course, to take the peak value.

In view of the aforementioned comments it is likely that a practical approach to RF exposure assessment in enterprises, especially small or medium-size ones with limited OSH resources, uses instantaneous peak values for E- and H-fields. Moreover, if necessary, 6-min time averaging is done before a comparison with the action values. Thus, no spatial averaging and no numerical calculations of specific cases, and the action values become practical limit values.

The assessment of induced currents resulting from hand-operated sources of a strong electric field or from contact of a worker's body with their elements (e.g., with an active electrode or a cable of an electrosurgery unit) is problematic. Very few commercially available instruments can measure the current flowing through the limbs (they are clamp-on or stand-on meters). Moreover, the assessment criterion is a problem in the case of EMF sources with frequencies <10 MHz. Directive 2004/40/EC does not set limits for the induced current in the limbs for such frequencies [8]. However, limitation of the local thermal effect in the limbs (local SAR) is provided for frequencies >100 kHz. These quantities may be assessed using the permissible values given in the directive for contact current or the permissible values for induced current in the feet specified in Standard No. C.95.1:2005 [2].

For industrial workers' exposure, a comparison of the provisions of Directive 2004/40/EC [8] with Standard No. C.95.1:2005 [2] shows that the practical differences are not big except for contact current and how it should be measured. Standard No. C.95.1:2005 is in favour of point contact, whereas ICNIRP [1] and Directive 2004/40/EC

[8] do not define it clearly. However, the level of permissible current suggests that grasp contact was considered. The only instrument that did not involve a person in actual measurements is no longer commercially available. This instrument had an add-on device to convert from a point contact to a grasp contact measurement. Now, without this instrument the only way to measure contact current is to use a clamp-on amp meter and to use the measuring person instead of a phantom connected to RF ground. A clamp-on meter can also be used for measuring induced currents in hands and legs.

For high-level exposure, only phantom-based measurements of contact and induced currents can be accepted for routine practice in the workplace. It is also very important for practical applications to provide more precise definitions of cases in which contact and induced current limitations should apply (e.g., how current in the hand of a nurse who is holding an insulated cable powering an electrosurgery electrode should be assessed).

8. NUMERICAL DOSIMETRY

Even though dosimetric computational results can represent complex exposure problems, they are affected by some intrinsic limitations. Different factors contribute to the unknown overall uncertainty; its dependence on the variation of each one has to be evaluated. Limited knowledge on the dielectric properties of human tissues at the lowest frequencies is a basic factor of uncertainty.

In situ measurements can be used for validating the results of numerical simulations that represent an exposure scenario. It is also possible to compare measurement results with calculation results for contact currents, induced currents (especially foot currents) and SAR from laboratory phantom measurements. To obtain accurate results on real situations, very high resolution models of the human body should be implemented for different ages, dimensions and phenotypes. For instance, an increase of whole-body SAR up to 25% has been reported for female models (compared to male ones), due to different content and distribution of fat tissue [31]. Such models should be also able to represent typical complex postures; whereas the ones available now represent the posture during MRI or a computed axial tomography (CAT) scan. There have to be methods for processing anatomical models to obtain different body postures: the effects on SAR have been observed up to 300 MHz [32]. Some methods are implemented in commercial packages, but the accuracy of the results needs to be carefully validated in a wide range of conditions.

Other problems affecting the accuracy of results are related to the numerical modelling of EMF sources. Information on the operation of the source of exposure can be poor in terms of physical or geometrical characteristics. For instance, modern welding machines have digitally controlled power electronic circuits that produce complicated current pulses, very difficult to detect with common measurements. Mobile phone base station antennas situated inside weather-proof welded plastic casings are another example. Those casings cannot be opened for visual inspection to observe the structure and type of radiating parts. Such information is often not easily available from the manufacturer and, in the worst cases, even regarded as a trade secret [33]. In these cases it is important to be able to assemble a model of the exposure scenario that safely overestimates exposure. This requires a good understanding of physics and the technology used in the device. The manufacturers of equipment could be, however, more active in this area. More active participation from trade unions would also help in determining what the worst-case exposure scenarios are for specific jobs.

Moreover, algorithms implemented in commercial packages have not been fully standardised or validated against one another, especially in the low frequency range. Standardised methods for estimating the applicability of an algorithm should be developed, too. At the same time, the algorithms for obtaining dosimetric quantities from raw electromagnetic results (e.g., the internal electric

field) have not been harmonised, so the user of a package cannot even find out what they are.

At the state-of-the art level, a detailed knowledge necessary for evaluating uncertainty in numerical dosimetry is not entirely available, and the accuracy of the results can be very poor, especially for complex exposure scenarios. This seriously limits the potential applicability of that technique in OSH systems in enterprises.

9. MANAGEMENT OF UNCERTAINTY

Uncertainty is defined as a "parameter associated with the results of a measurement that characterizes the dispersion of the values that could reasonably be attributed to the measurand" (point 3.9) [34]. In other documents the term inaccuracy, too, can be found in the context of the dispersion of measurement results.

In general, uncertainty is defined as lack of knowledge about the true value of real exposure, which might be caused by measurement errors or other factors of the entire exposure assessment scenario. Uncertainty is often confused with variability, so it is important to stress that variability is a property of nature that is related to heterogeneity, homogeneity or consistency of values over time, space and subjects. Because there is always a distinction between variability and uncertainty, the two concepts have to be handled separately.

Uncertainty plays an important role in assessing human exposure to EMF since it affects the results of measurements and numerical calculations. Directive 2004/40/EC does not discuss the problem of uncertainty in the compliance judgement [8]. However, Directive 2003/10/EC indicates that "the assessment of the measurement results shall take into account the measurement inaccuracies determined in accordance with metrological practice" (article 4) [35]. It seems reasonable to extend that approach to EMF exposure assessment.

According to the World Health Organization (WHO) "uncertainty in measurements used to evaluate compliance is a practical problem best handled by organizations responsible for the development of compliance methods" (p. 28). Standards developed by international, regional, and national technical bodies such as International Electrotechnical Commission (IEC), International Organization for Standardization (ISO), CENELEC, etc., "can provide technical advice on how to conduct compliance measurements" (p. 27) [36]. Technical standards also give typical sources of uncertainties, both for measurement and numerical methods, and data on typical scales of particular components to help estimate total uncertainty. It should be noted that uncertainty estimation is a pure technical/scientific subject. The legal interpretation of measurement results and their uncertainty against limit values and identification of overexposure cases are separate issues.

The management of uncertainty in the compliance judgement with exposure limits, in the context of human exposure assessment, is still an open question. The need for a clear indication from authorities is manifest in the final draft Standard No. prEN 50499:2008 developed under European Commission's mandate M/351 for application of Directive 2004/40/EC [37]. This standard, in addition to indicating that uncertainty analysis is necessary, reports that measurements and/or calculations of uncertainty have to be taken into account "according to national regulation in relation to the implementation of the directive" (p. 28) [38].

However, Directive 2004/40/EC states that "in any event, workers shall not be exposed above the exposure limit values" (article 5, point 4) [8]. The strategy for analysis of exposure assessment results should ensure compliance with that provision.

At the moment only generic and basic standards applicable to the emission of specific products or families of products offer practical advice on how to treat uncertainty. Recommendations are mostly based on the shared uncertainty budget approach, but the criteria outlined are not always uniform. Few standards require uncertainty to be included in a comparison with an exposure limit [16, 39]. The prevailing indication is, however, that uncertainty must be assessed and reported, but measurements or calculation results should be

directly compared with the limits, provided that overall uncertainty is lower than a recommended value. To support this approach, some standards invoke the presence of safety factors in the setting of basic restrictions and reference levels in the protection guidelines [19, 28, 40, 41, 42]. Such an argument could be controversial, as according to ICNIRP guidelines [1] other variables are considered in the development of safety factors, such as (for high-frequency fields) the effects of EMF exposure under severe environmental conditions; potentially higher thermal sensitivity in certain population groups; differences in absorption of electromagnetic energy by individuals; and reflection, focusing, and scattering of the incident field.

The shared uncertainty budget (or shared risk) approach, which is explained well in LAB34 [43], implies that the actual measured or calculated values must be used for comparison with exposure guidelines, provided that the total assessed uncertainty is lower than or equal to permissible or reasonable predefined uncertainties, or if the assessment is proven to always overestimate exposure. Uncertainty values should be recorded but should not be included in the comparison. Typical permissible uncertainties defined in relevant standards range from ±2 dB (+26%, –21%) to ±6 dB (+100%, –50%) for field measurements, and are of the order of ±50% for calculation. If the expanded uncertainty is higher than permissible values, the applicable limit for verification of compliance must be reduced by a specific factor, as established in Standard No. EN 50392:2004 [44].

From the philosophical point of view, the shared risk approach, as intended in electromagnetic compatibility (EMC) testing, is applicable when the end user or the authority responsible for control makes a judgement on compliance and accepts some of the risk that the product may not meet the specification. Generally, this is acceptable in nonsafety critical performance. That is why the shared uncertainty budget approach to verifying human exposure compliance (not product standardization) should be considered acceptable only if the authorities responsible for control and application of sanctions have explicitly indicated so.

In Italy, Standard No. CEI 211-7:2001 addresses the issue of ways of dealing with uncertainty in measurements with reference to human exposure [45]. It points out that, if measurement uncertainty is limited to a maximum value of ±3 dB (+41%, –29%), field levels can be directly compared with exposure limits. Uncertainty values must be always recorded in the measurement report and measurements with uncertainties greater than ±3 dB have to be considered suggestive. They can be used only when they differ from exposure limits by a quantity greater than uncertainty itself; otherwise, measurements with better accuracy are needed. The Italian Prime Minister's decree of 8 July 2003, establishing the limits of exposure for the protection of population from EMF in the frequency range of 100 kHz–300 GHz, adopts this shared risk principle through reference to Standard No. CEI 211-7:2001 as a technical reference for measurements and evaluations of exposure.

In practice, the minimum recommended (in product standards) permissible uncertainties for field measurements are of the same order of magnitude as for typical performance of instrumentation usually used in assessment. On the other hand, computational permissible uncertainties seem optimistic when compared with realistic evaluations. Bahr, Boltz and Hennes estimated computational uncertainties by comparing numerical results with analytical solutions for simple-shaped models [46]. They found the value of ±12.2 dB (+307%, –75%) for worst-case expanded uncertainties (95% confidence interval) in determining in situ electric fields and current densities. The finite difference time domain method was used in computations.

The poor reliability of numerical dosimetry becomes a critical issue especially in in vitro and in vivo experiments, where dosimetry is used to evaluate the response of biological systems to exposure to EMF. This high accuracy requirement is stressed in EMF-NET's report, which highlights the need for an experimental verification of numerical dosimetry results for

in vitro and in vivo experiments [47]. Such high accuracy is not equally relevant in occupational exposure assessment, where numerical dosimetry is used to verify compliance with limits.

Some conclusions can be drawn in the context of policy indications for managing uncertainty in assessing workers' exposure and verifying compliance with regulations. For field measurements, the shared uncertainty budget approach could be practicable if explicitly recommended by authorities, and provided that maximum permissible uncertainty does not exceed ±3 dB in the whole frequency range. However, such practice can lead to administrative acceptance of an individual worker's exposure exceeding an action level, even significantly, depending on the decision of what confidential interval should be considered for uncertainty analysis (e.g., 95 or 99%).

The strongest demands for an analysis of uncertainty come from mandatory legislation of the threshold type, according to which exceeding the EMF threshold (fixed by legislation) automatically leads to serious administrative consequences, e.g., fines or an obligation to switch off the EMF emitting devices [22]. In such cases, it is necessary to analyse in detail the uncertainty of assessment as well the arbitrary decision on the maximum acceptable uncertainty and on the decision model (e.g., shared uncertainty). In contrast, the lowest requirements for the uncertainty analysis come from the continuous quality improvement type of legislation, standards or guidelines (e.g., a voluntary system of management of OSH hazards). In such cases, the results of EMF assessment should be always analysed in the context of a possible reduction in EMF, but the reduction should be greater and is more urgent when the level of EMF is higher. In such a model, the level of uncertainty can be accepted even at a very high value and does not have to be calculated in detail. The only important requirement is that properly executed and harmonised EMF identification, selection of assessment criteria, measurement device and measurement protocol can all be guaranteed.

Basic knowledge necessary to assess the uncertainty of numerical dosimetry, both in low

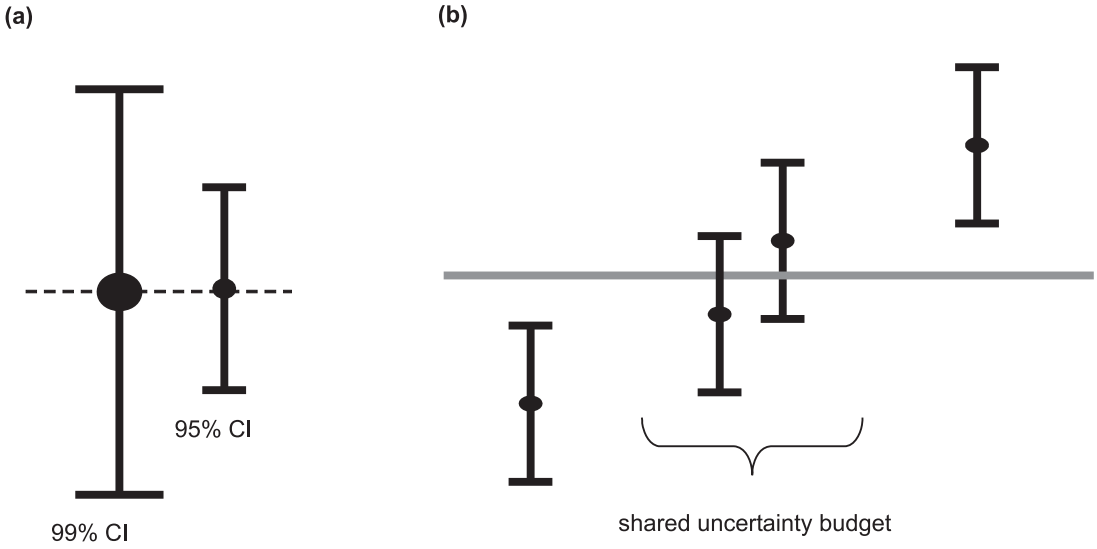

Figure 11. Illustration of the open questions and different approaches to the uncertainty problem: (a) the technical problem of how to assess confidential interval (CI) for the measurement results (dotted line); (b) the systematic or political problem of how to interpret measurement results, including their uncertainty, against the limit value (solid line) and when to indicate overexposure. *Notes.* Depending on who has ordered the measurements the approach can be different and uncertainty bars can be acceptable on different sides of the limit value. For example, if the measurements are done for the employer, the values have to be lower than the limit to ensure that exposure is below the limits. If the labour inspectorate is checking the parameters of occupational exposure, values exceeding the limit can fully justify legal actions to avoid workers' exposure to hazards.

and high frequency ranges, is not fully available yet. This is so, especially for complex exposure conditions where the accuracy of results can be very poor. To produce interpretable results, numerical dosimetry should be limited to obtaining information for standard and traceable worst-case conditions. Considering the strongly conservative nature of calculation, realistic high values for permissible uncertainties could be accepted in a shared risk approach (Figure 11).

However, the limit setting organisation must also state if, e.g., 95 or 99% confidence limits should apply. The shared uncertainty budget can only be applied if the estimated errors are low, which is usually not the case in occupational exposure assessment.

10. ACCREDITATION

Another identified problem is exposure assessment carried out by people with insufficient knowledge about and/or experience in physics, instrumentation and statistics related to EMF. There have been many reports of people trying to take microwave measurements with ELF instruments, people claiming exposure was several times above the limit in ELF magnetic fields in the nanotesla range. One way of reducing the number of such misinterpretations is to demand an accreditation from those providing commercial services related to measuring exposure to show compliance with the directive. It is also possible to at least demand documented basic knowledge of instrumentation, measurement techniques, fundamental knowledge on the biological effects of exposure to EMF, and periodic calibration of instruments. Setting up an accreditation system is a complicated task, which will take years before it is efficient. However, some solution imposing restrictions on amateurs is called for.

11. HEALTH SURVEILLANCE

The provision for health examinations for workers who have been overexposed is still a point that needs to be addressed. Where exposure above the exposure limit values is detected, medical examinations should be made available for the worker or workers concerned in accordance with national laws and practices. It is important to note that it is not action levels but exposure limits in terms of current density or SAR that are relevant. This means that to verify that there has been overexposure, numerical calculations are necessary. This is not likely to happen, and even if it did, those calculations would take several weeks. This would limit the physician's possibility of conducting any meaningful examinations. Therefore, health surveillance requirement in Directive 2004/40/EC should be changed so that there are medical examinations whenever action levels are exceeded [8].

Unfortunately, except for localised skin burns, there is little objective medical evidence indicating immediately possible overexposure. Localised heating sensations or burns occur near metallic objects, such as jewellery, and medical and dental implants. Other RF overexposure symptoms include localised pain, reddening of the skin, elevated body temperature and fatigue. Even when workers are not overexposed, they can exhibit acute anxiety reactions (with accompanying nausea and headaches), if they suspect overexposure. It is much more difficult for workers to notice the effects of overexposure in the low frequency range, except for sensations like phosphenes or vertigo.

An initial medical examination should be conducted when a worker is hired. If the worker has medical implants and anticipates working near EMF sources, potential EMF interference with these devices/systems should be evaluated (cf. Hocking and Hansson Mild for a further discussion on this [48]).

Training is an important part of preventing overexposure of personnel. EMF safety awareness training is required for all workers who might be overexposed, and for managers who supervise those workers. The key elements of the training are to help personnel to recognise situations with potential overexposure, and to understand ways of avoiding it. Other aspects of training can include potential EMF interference with medical implants, EMF biological effects/hazards, EMF warning signs and alarms, and overexposure incident procedures.

12. MEDICAL IMPLANTS

Directive 2004/40/EC states in its preamble that "Adherence to the exposure limit and action values may not necessarily avoid interference problems with, or effects on the functioning of, medical devices such as metallic prostheses, cardiac PM and defibrillators, cochlear implants and other implants; interference problems especially with PM may occur at levels below the action values and should therefore be the object of appropriate precautions and protective measures" (p. 4) [8]. Nevertheless, protection from all indirect effects (including electromagnetic interferences, EMI) is incorporated in the provisions on risk assessment (article 4, point 5d) even without giving limits for preventing such effects, and the employer is called upon to make a specific evaluation for workers at particular risk (article 4, point 5c). Appropriate precautions should be then undertaken, mostly based on signs and keeping susceptible workers far away from the source.

Concerning implantable medical devices, cardiac PM and defibrillators (implantable cardioverter defibrillator, ICD) are the main health concerns. PM and defibrillators are able to detect the heart's electric activity (the sensing function) and stimulate it (the pacing function) when it is inadequate or pathological. The issue of a possible malfunction of such devices due to EMI must be suitably taken into account because of its severe negative potential, above all for patients dependent on their correct operation. The technological evolution aimed at improving the performance of these devices has involved an increasing sensitivity to EMI. In particular, the sensing function, introduced to avoid conflict between pacing and regular cardiac activity, has made PM and ICD more vulnerable.

EMI on PM and defibrillators has been investigated worldwide for several years; the greatest concerns have arisen from the large diffusion of telecommunication systems, primarily cellular phones. Studies assessed the real risk, the mechanisms involved and the countermeasures to be taken. Particular attention was focused on EAS, medical devices, and radio frequency identification (RFID) systems such as telecommunication facilities and mobile phones. Several experiments in vivo and in vitro showed there was little probability of EAS and medical devices interfering, with transient EMI effects in most cases not clinically significant for patients. Similar results were reported for RFID operating at 120 kHz CW (continuous wave).

According to numerous studies GSM mobile phones interfered with PM, due to the low frequency components (2.2, 8.3 and 217 Hz), especially during ring and handover phases [49]. The duration of a malfunction is generally limited to the duration of interference and is followed by renewal of normal operation. Incorrect inhibition or triggering of stimulation, reversion to asynchronous pacing and incorrect detection of tachyarrhytmia may result from the effect of EMI on PM and ICD. Less frequent effects may consist in reprogramming of operating parameters or permanent damage to circuitry. An investigation on the effects of EMI on medical devices used in hospitals indicated that mobile phones could cause disturbance at a distance of several metres from the most sensitive equipment [50].

Regarding product regulation, safety requirements for active implantable medical devices (AIMD) are established by Directive 90/385/EEC [51], modified by Directive 2007/47/EC [52]. The relevant harmonised standards are Standard No. EN 45502-2-1:2003 [11] and No. EN 45502-2-2:2008 [13]. Focusing on PM, the standards describe tests that should be done for both conducted and radiated effects, to verify the immunity of the devices. Requirements on electromagnetic immunity are given both for static magnetic fields and for time-varying electromagnetic fields, in the frequency range from 16.6 Hz (railway traction power lines) to 3 GHz, to take into account exposure to common widespread sources, including mobile phones and telecommunication plants, EAS systems and many others. The standard does not cover exposure to therapeutic and diagnostic treatments. For signals and fields from special industrial equipment, the standard refers to particular assessments to be performed in co-operation with the manufacturer.

To prevent interference with cardiac stimulators, ICNIRP guidelines on static

magnetic fields [4] recommend patients to avoid exposure exceeding a magnetic flux density of 0.5 mT, whilst protection from EMI is not addressed in the 1998 ICNIRP guidelines on time-varying fields [1]. Standards No. EN 45502-2-1:2003 [11] and No. EN 45502-2-2:2008 [13] raise this ceiling value establishing that PM should not be affected by static magnetic fields of flux density of up to 1 mT. On the other hand, the American Conference of Governmental Industrial Hygienists also gives the limit of exposure of 0.5 mT for static magnetic fields, and indicates the levels of exposure up to 1 kV/m and 100 μT (rms values) to 50/60-Hz electric and magnetic fields [12]. However, EMI thresholds for 50-Hz electric fields are lower than corresponding limits for protecting against the direct effects of the induction of currents.

Under European Commission's mandate M/351, CENELEC is working on a specific standard (prEN 50527-1) addressed to outline a general methodology of risk exposure evaluation for workers bearing AIMD [37]. The basic idea, currently under discussion, is that AIMD are expected to operate correctly if levels of exposure do not exceed the general-public reference levels of recommendation 1999/519/EC [53]. For risk evaluation purposes an exclusion list of automatically compliant equipment is defined, while specific assessment is required for equipment not present on that list. This approach cannot, however, guarantee that all PM currently implanted in patients comply with the requirements defined in Standard No. EN 45502-2-1:2003; some devices were put on the market before its publication [11]. Moreover, even when an AIMD complies with a relevant standard, the immunity of the device cannot be guaranteed considering all the signals and frequencies present in the work and life environments. Interference with medical devices should be monitored and research should be updated. It is necessary to review data on EMF and PM and other implantable devices to be able to solve the following problems:

- Possible interference between E- and B-fields in different frequency bands and PM, ferromagnetic implants and other electronic implants.
- What is the probability of an interference event when the direct current (DC) B-field threshold of 0.5 mT is exceeded? Which modal event will take place?
- Can strong static E-fields related to an electrostatic discharge trigger such interference?
- What is the interference threshold for an ELF B-field? Is it 200 μT? What is the probability of an interference event?
- Are there well-defined interference thresholds for IF and RF fields?

Users need the access to data concerning the immunity of each device, even if at the time of implantation they are not involved in EMF-related activities. They might need to start such activities, for professional or personal reasons, in the future.

13. MITIGATION AND SHIELDING

For cases of overexposure in the workplace, there are also important questions on the effectiveness of mitigation in high-exposure technology. Those questions are also pertinent, though, for the general public in the public environment (e.g., in means of public transport).

Mitigation is a common term for reducing exposure to electromagnetic fields. It covers shielding with ferromagnetic and/or conductive materials on the one hand and field reduction using passive or active cancellation wire loops on the other. Ferromagnetic material shielding creates an alternative path for the magnetic flux. Conductive materials can create magnetic fields of opposite polarisation; depending on the phase angle, they cancel to a greater or lesser extent the total magnetic flux density of exposure in a particular space.

Mitigation may be used to avoid interference of the magnetic field with sensitive equipment (e.g., distortion of working stations by the static field of MRI, or electrolysis processes) and perhaps to protect workers against occupational enhanced EMF levels. DC or AC magnetic shielding for avoiding distortion of working stations in electrolysis or ELF applications is

easy to perform by enclosing it in a mu-metal[1] three-walled box system (magnetic shielding). However, when we want to mitigate workers, magnetic field shielding becomes much more complex. Indeed, shielding of operators by enclosing them in a mu-metal box system is impossible because of discomfort. Operators' protecting clothes for mitigating DC or ELF magnetic fields do not exist; moreover, a low frequency reducing clothing fibre is very difficult and expensive to develop. Perhaps, by taking into account the risk of occupational overexposure to EMF, it is possible to develop power installations such as new induction furnaces, arc ovens, etc., in which all or most mitigation requirements are fulfilled. Anyway, how should we deal with older installations constructed before architecture was aware of possible EMF-risks and which are installed in few working places only? Should such installations be replaced with expensive new ones that fit the EMF-risks concept?

How should mitigation be applied on smaller high-exposure sources such as, e.g., welding equipment and magnetic re-activators in libraries? These examples illustrate the open questions that mitigation and shielding involve. However, because there are no relevant data or research, no answers can be given at present.

14. CONCLUSIONS AND RECOMMENDATIONS

Directive 2004/40/EC [8], based on the ICNIRP guidelines [1], was to be implemented in Member States by 2008. Because of some unexpected problems the deadline of implementation was postponed until 2012. This paper reviews some of the problems identified and also presents some suggestions for possible solutions based on the authors' experience in assessing occupational EMF exposure.

Directive 2004/40/EC gives an exposure limit for induced current density of 40 mA/m^2 for exposure to fields with frequency <1 Hz [8]. The action level is set at 200 mT but no value is given for static magnetic fields ($f = 0$ Hz). Movement in the static field produces induced currents. These should be treated in the same way as currents resulting from exposure to a time-varying magnetic field. At the moment it is not clear if this is the case.

The limits for exposure to ELF fields are set to protect against nerve excitation, which can happen during exposure <10 ms. However, the limits are set in rms and the same applies to the corresponding time to be used in assessing induced current density and contact current. The IEEE standard [3] gives the rms averaging time as the longer of 0.2 s or 5 cycles (up to 10 s). For spot welding the total welding time is typically shorter than one second. The whole weld is over before the averaging time is up. When discussing handheld tools, the CENELEC standard [16] states that the first 200 ms should be neglected. The machine usually draws 10 times more current during the first few periods. The aim of Directive 2004/40/EC is to protect against nerve excitation and this exception is in conflict with the biomedical rationale for safety guidance [8].

The difference between the emission and exposure standards is another problem that is discussed. Emission standards are created to provide standardised procedures for laboratory testing. Exposure standards are applicable to the real work environment and the measurements should refer to the worst-case exposure scenario. The use of CENELEC emission standards [16, 19, 20] is therefore problematic in exposure assessments.

At power frequency electric fields limit set by Directive 2004/40/EC is 10 kV/m as the highest value for working in a 50-Hz environment [8]. However, the ICNIRP guidelines [1] make increasing the limit twofold possible, if the worker is not in contact with electrical grounds, since the limit here is based on avoiding spark discharges rather than induced current density limit. Work in existing high-voltage switchyards, of which there are many hundreds of thousands all over Europe, may be problematic with the low 10 kV/m limit.

[1] a highly permeable nickel-iron alloy

Some of the aforementioned questions require an arbitrary administrative decision, but for others further research is necessary. How should exposure be assessed in the vicinity of a EMF source of a dynamically-changing geometry and EMF emission level (e.g., welding devices)? Can limb current be exceeded although E-field value is below the action level? When is it necessary to use spectrum analysers? What are the requirements regarding conditions of measurements representing real exposure of workers?

The basic problems related to calculating a representation of workers' exposure level are correct representations (a) of the realistic posture of a worker's body; (b) of the electrical grounding conditions at the workplace; (c) of realistic impedance of near-field produced by, e.g., electrosurgery or welding devices; and (d) of dynamic changes in EMF level in the course of application. Proper calculations in assessing exposure require advanced skills, specialised software and can be both very time-consuming and expensive. Validation and verification of the skills of personnel who do the calculations are also necessary.

A common practice in expressing the uncertainty in measurements and numerical simulations performed to assess workers' EMF exposure has not been established yet.

REFERENCES

1. International Commission on Non-Ionizing Radiation Protection (ICNIRP). Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 300 GHz). Health Phys. 1998; 74(4):494–522.
2. Institute of Electrical and Electronics Engineers (IEEE). IEEE standard for safety levels with respect to human exposure to radio frequency electromagnetic fields, 3 kHz to 300 GHz (Standard No. C.95.1:2005). New York, NY, USA: IEEE; 2005.
3. Institute of Electrical and Electronics Engineers (IEEE). IEEE standard for safety levels with respect to human exposure to electromagnetic fields, 0–3 kHz (Standard No. C.95.6:2002). New York, NY, USA: IEEE; 2002.
4. International Commission on Non-Ionizing Radiation Protection (ICNIRP). Guidelines on limits for exposure to static magnetic fields. Health Phys. 1994;66(1):100–6.
5. Hansson Mild K, B. Greenebaum. Environmental and occupationally encountered electromagnetic fields. In: Barnes FS, Greenebaum B, editors. Handbook of biological effects of electromagnetic fields. 3rd ed. (Vol. 1. Bioengineering and biophysical aspects of electromagnetic fields). Boca Raton, FL, USA: CRC Press; 2007. p. 1–34.
6. Hietanen M, Hansson Mild K, Karpowicz J. Exposure to electromagnetic fields in the work environment and basic measurement problems. In: Kostarakis P, editor. Biological Effect of EMFs. 3rd International Workshop. Proceedings. University of Ioannina and NCSR Demokritos; 2004. p. 1174–80.
7. Karpowicz J, Gryz K. Practical aspects of occupational EMF exposure assessment. Environmentalist. 2007;27:525–31.
8. Directive 2004/40/EC of the European Parliament and of the council on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (electromagnetic fields). OJ. 2004;L159:1–26.
9. International Electrotechnical Commission (IEC). Medical electrical equipment. Part 2. Particular requirements for the safety of magnetic resonance equipment for the safety of magnetic resonance equipment for medical diagnosis (Standard No. IEC-601-2-33:1995). Geneva, Switzerland: IEC; 1995.
10. European Committee for Electrotechnical Standardization (CENELEC). Medical electrical equipment. Part 2: particular requirements for the safety of magnetic resonance equipment for medical diagnosis (Standard No. EN 60601-2-33:2002). Brussels, Belgium: CENELEC; 2002.
11. European Committee for Electrotechnical Standardization (CENELEC). Active implantable medical devices—part 2-1: particular requirements for active implantable medical devices intended to

treat bradyarrhythmia (cardiac pacemakers) (Standard No. EN 45502-2-1:2003). Brussels, Belgium: CENELEC; 2003.

12. American Conference of Government Industrial Hygienist (ACGIH). Threshold limit values and biological exposure indices. Cincinnati, OH, USA: ACGIH; 2008.
13. European Committee for Electrotechnical Standardization (CENELEC). Active implantable medical devices—part 2-2: particular requirements for active implantable medical devices intended to treat tachyarrhythmia (includes implantable defibrillators). (Standard No. EN 45502-2-2:2008). Brussels, Belgium: CENELEC; 2008.
14. Reilly JP. Applied bioelectricity. From electrical stimulation to electropathology. New York, NY, USA: Springer-Verlag. 1998.
15. European Committee for Electrotechnical Standardization (CENELEC). Basic standard for evaluation of human exposure to electromagnetic fields from equipment for resistance welding and allied processes (Standard No. prEN 50505:2007). Brussels, Belgium: CENELEC; 2007.
16. European Committee for Electrotechnical Standardization (CENELEC). Measurement methods for electromagnetic fields of household appliances and similar apparatus with regard to human exposure (Standard No. EN 62233:2008). Brussels, Belgium: CENELEC; 2008.
17. Estenberg U, Anger G, Trulsson J. Kartläggning av exponering för magnetfält runt larmbågar och RFID-system (SSI Report No. 2006:3). Stockholm, Sweden: Swedish Radiation Protection Authority; 2006. With a summary in English. Retrieved November 15, 2008, from: http://www.stralsakerhetsmyndigheten.se/Global/Publikationer/Rapport/Str%C3%A5lskydd/2006/ssi-rapp-2006-03.pdf
18. Trulsson J, Anger G, Estenberg U. Assessment of magnetic fields surrounding electronic article surveillance systems in Sweden. Bioelectromagnetics. 2007;28(8): 664–6.
19. European Committee for Electrotechnical Standardization (CENELEC). Evaluation of human exposure to electromagnetic fields from devices used in electronic article surveillance (EAS), radio frequency identification (RFID) and similar applications (Standard No. EN 50357:2001). Brussels, Belgium: CENELEC; 2001.
20. European Committee for Electrotechnical Standardization (CENELEC). Basic standard for the evaluation of human exposure to electromagnetic fields from equipment for arc welding and allied process (Standard No. EN 50444:2008). Brussels, Belgium: CENELEC; 2008.
21. International Commission on Non-Ionizing Radiation Protection (ICNIRP). Guidance on determining compliance of exposure to pulsed fields and complex non-sinusoidal waveforms below 100 kHz with ICNIRP guidelines. Health Phys. 2003;84(3):383–7.
22. Karpowicz J, Gryz K. Health risk assessment of occupational exposure to a magnetic field from magnetic resonance imaging devices. International Journal of Occupational Safety and Ergonomics (JOSE). 2006;12(2):155–67.
23. Jokela K. Restricting exposure to pulsed and broadband magnetic fields. Health Phys. 2000;79(4):373–88.
24. Jokela K. Assessment of complex EMF exposure situations including inhomogeneous field distribution. Health Phys. 2007;92(6):531–40.
25. Koradecka D, Pośniak M, Jankowska E, Skowroń J, Karpowicz J. Chemical, dust, biological and electromagnetic radiation hazards. In: Salvendy G, editor. Handbook of human factors and ergonomics. 3rd ed. New York, NY, USA: Wiley; 2006. p. 945–64.
26. Corrigendum to Directive 2004/40/EC of the European Parliament and of the Council of 29 April 2004 on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (electromagnetic fields) (18th individual Directive within the meaning of Article 16(1) of Directive 89/391/EEC). OJ. 2004;L184:1–9.
27. Wilén J, Hörnsten R, Sandström M, Bjerle P, Wiklund U, Stensson O, Lyskov E, Hansson Mild K. Electromagnetic field exposure and health among RF plastic sealer operators. Bioelectromagnetics. 2004;25:5–15.

28. European Committee for Electrotechnical Standardization (CENELEC). Limitation of human exposure to electromagnetic fields from devices operating in the frequency range 0 Hz to 10 GHz, used in Electronic Article Surveillance (EAS), Radio Frequency Identification (RFID) and similar applications (Standard No. EN 50364:2001). Brussels, Belgium: CENELEC; 2001.
29. Gryz K, Karpowicz J, Molenda M, Zradziński P. Numerical simulations of EMF from dielectric heaters and comparative analysis of Directive 2004/40/EC and occupational regulation in Poland. In: Proceedings of 18th International Wrocław Symposium and Exhibition on Electromagnetic Compatibility. Wrocław, Poland: Oficyna Wydawnicza Politechniki Wrocławskiej; 2006. p. 95–9.
30. Polski Komitet Normalizacyjny (PKN). Labour protection in electromagnetic fields and radiation of the frequency range from 0 Hz to 300 GHz. Part 1. Terminology. Part 3. Methods of measurements and evaluation of field on the work stands (Standard No. PN-T-06580:2002). Warszawa, Poland: PKN; 2002. In Polish.
31. Sandrini L, Vaccari A, Malacarne C, Cristoforetti L, Pontalti R. RF dosimetry: a comparison between power absorption of female and male numerical models from 0.1 to 4 GHz. Phys Med Biol. 2004;49: 5185–201.
32. Findlay RP, Dimbylow PJ. Effects of posture on FDTD calculations of specific absorption rate in a voxel model of the human body. Phys Med Biol. 2005; 50:3825–35.
33. Alanko T, Hietanen M. Occupational exposure to RF fields in antenna towers. Radiat Prot Dosimetry. 2007;123:537–9.
34. International Organization for Standardization (ISO). International vocabulary of basic and general terms in metrology. Geneva, Switzerland: ISO; 1993.
35. Directive 2003/10/EC of the European Parliament and of the Council of 6 February 2003 on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (noise). OJ. 2003;L42.
36. World Health Organization (WHO), Framework for developing health-based EMF standards. Geneva, Switzerland: WHO; 2006. Retrieved November 15, 2008, from: http://www.who.int/peh-emf/standards/EMF_standards_framework%5b1%5d.pdf
37. European Commission. Employment and Social Affairs DG. Standardisation mandate addressed to CEN, CENELEC and ETSI to develop harmonised standards for the assessment, measurement and calculation of workers' exposure to static magnetic and varying electric, magnetic and electromagnetic fields with frequencies from 0 Hz to 300 GHz (EMPL/D-4/AF/D(2004); M/351); Luxembourg, 17 May 2004. Retrieved November 15, 2008, from: http://ec.europa.eu/enterprise/standards_policy/mandates/database/index.cfm?fuseaction=search.detail&id=229#
38. European Committee for Electrotechnical Standardization (CENELEC). Procedure for the assessment of the exposure of workers to electromagnetic fields (Standard prEN 50499:2008). Brussels, Belgium; CENELEC; 2008.
39. European Committee for Electrotechnical Standardization (CENELEC). Household and similar electrical appliances—electromagnetic fields—methods for evaluation and measurement (Standard No. EN 50366:2003). Brussels, Belgium; CENELEC; 2003.
40. European Committee for Electrotechnical Standardization (CENELEC). Product standard to demonstrate the compliance of mobile phones with the basic restrictions related to human exposure to electromagnetic fields (300 MHz–3 GHz) (Standard No. EN 50360:2001). Brussels, Belgium; CENELEC; 2001.
41. European Committee for Electrotechnical Standardization (CENELEC). Product standard to demonstrate the compliance of radio base stations and fixed terminal stations for wireless telecommunication systems with the basic restrictions or the reference levels related to human exposure to radio frequency electromagnetic fields (110 MHz–40 GHz)—occupational

(Standard No. EN 50384:2002). Brussels, Belgium; CENELEC; 2002.

42. European Committee for Electrotechnical Standardization (CENELEC). Product standard to demonstrate the compliance of radio base stations and fixed terminal stations for wireless telecommunication systems with the basic restrictions or the reference levels related to human exposure to radio frequency electromagnetic fields (110 MHz–40 GHz)—general public (Standard No. EN 50385:2002), Brussels, Belgium: CENELEC; 2002.
43. LAB34. The expression of uncertainty in EMC testing. Feltham, Middlesex, United Kingdom Accreditation Service (UKAS); 2002. Retrieved November 15, 2008, from: http://www.ukas .com/Library/downloads/publications/Lab34.pdf
44. European Committee for Electrotechnical Standardization (CENELEC). Generic standard to demonstrate the compliance of electronic and electrical apparatus with the basic restrictions related to human exposure to electromagnetic fields (0 Hz–300 GHz) (Standard No. EN 50392:2004). Brussels, Belgium: CENELEC; 2004.
45. Italian National Electrotechnical Committee (CEI). Guide for the measurement and the evaluation of electromagnetic fields in the frequency range 10 kHz–300 GHz, with reference to the human exposure (Standard No. CEI 211-7:2001). Milan, Italy: CEI; 2001. In Italian.
46. Bahr A, Boltz T, Hennes C. Numerical dosimetry ELF: accuracy of the method, variability of models and parameters, and the implication for quantifying guidelines. Health Phys. 2007;92(6):521–30.
47. EMF-NET. Sixth Framework Programme. Recommendations on engineering requirements/aspects for experimental research in bioelectromagnetics. Recommendations on quality assurance in bioelectromagnetics research (Project No. SSPE-CT-2004-502173); 2006. Retrieved November 15, 2008, from: http://web .jrc.ec.europa.eu/emf-net/doc/Reports/Report%20on%20Reccomendation%20in%20Bioelectromagnetcs%20Aug2006.pdf
48. Hocking B, Hansson Mild K. Guidance note: risk management of workers with medical electronic devices and metallic implants in electromagnetic fields. International Journal of Occupational Safety and Ergonomics (JOSE). 2008;14(2):217–22.
49. Barbaro V, Bartolini P, Donato A, Militello C, Altamura G, Ammirati F, Santini M. Do European GSM mobile cellular phones pose a potential risk to pacemaker patients? PACE. 1995;18:1218–24.
50. Hietanen M, Sibakov V. Electromagnetic interference from GSM and TETRA phones with life-support medical devices. Annals of Italian Institute of Health. 2007;43(3):204–7.
51. Council Directive 90/385/EEC of 20 June 1990 on the approximation of the laws of the Member States relating to active implantable medical devices. OJ. 1990; L189:17–36.
52. Directive 2007/47/EC of the European Parliament and of the Council of 5 September 2007 amending Council Directive 90/385/EEC on the approximation of the laws of the Member States relating to active implantable medical devices, Council Directive 93/42/EEC concerning medical devices and Directive 98/8/EC concerning the placing of biocidal products on the market. OJ. 2007;L247:21–55.
53. Council of the European Union Recommendation of 12 July 1999 on the limitation of exposure of the general public to electromagnetic fields (0 Hz to 300 GHz), 1999/519/EC. OJ. 1999:L199:59–70.
54. Karpowicz J, Hietanen M, Gryz K. Occupational risk from static magnetic fields of MRI scanners. Environmentalist. 2007;27:533–8.
55. Directive 2006/95/EC of the European Parliament and of the Council of 12 December 2006 on the harmonisation of the laws of Member States relating to electrical equipment designed for use within certain voltage limits (codified version). OJ. 2006; L374:10–9.
56. Directive 2004/108/EC of the European Parliament and of the Council of 15 December 2004 on the approximation of the laws of the Member States relating to electromagnetic compatibility and repealing Directive 89/336/EEC. OJ. 2004;L390:24–37.

APPENDIX

Highly exposed workers and workers at particular risk

Risk assessment of occupational exposure to EMF for highly exposed workers and workers at particular risk (pregnant workers, workers with metallic active or passive medical implants, young workers and other vulnerable workers) requires special methods. Directive 2004/40/EC also indicates the need for special attention in assessing occupational risk for those workers [8]. OSH engineers and employers require detailed advice to conduct such assessment in practice.

Attention should be paid to exposure characteristics of various groups of workers and various categories of realistic exposure scenarios with respect to noncompliance or compliance of the level of exposure at the workplace:

1. Highly exposed groups. Some technologies will require detailed investigation, and are the most likely cases of noncompliance with exposure limitations (Table 2). Internal measures of exposure assessment should be investigated for such workers, usually with computational procedures. An important piece of advice for OSH practice is to consider only trained workers to participate in occupational activities in highly exposed workplaces. EMF exposure warning signs, labelling EMF sources and informing workers about possible EMF hazards should be introduced, too. Suitable identification of such cases of exposure is crucial for OSH practice. The time that even well-trained workers can stay in an overexposed zone where source mitigation is difficult is another example of insufficient OSH knowledge. Although Directive 2004/40/EC states that protective actions should be taken, the details have not been specified yet [8].
2. Possibly exposed groups. Most technologies are likely to require assessment but include a few cases of noncompliance (Table 2). In most cases measurements of EMF exposure patterns are usually sufficient. The practice of involving only trained workers in occupational activities, EMF exposure warning signs, labelling of EMF sources and informing workers about possible EMF hazards could also be considered.
3. Groups not exposed. Many technologies will probably not require further assessment, with exposure levels under exposure guidelines (Table 2). In such workplaces, detailed exposure assessment is usually not needed. EMF emission assessment, e.g., product testing following the requirements of European standards harmonized with low voltage (LV) [55] or electromagnetic compatibility (EMC) [56] European directives, is enough in OSH practice. Usually there is no need for training and informing workers about EMF hazards, but in some cases warning signs can be important to avoid indirect EMF hazards or risk for particular groups of workers (e.g., hazard caused by static magnetic fields for people with cardiac pacemakers or explosive hazards caused by currents induced in metallic structures by shortwave EMF).

Cases 1 and 2 of exposure to EMF can be called occupational EMF exposure, case 3 can be called nonoccupational EMF exposure. It usually occurs in the workplace where the EMF exposure level is at a level typical for general-public and open environment exposure.

The overall conclusions regarding the impact of Directive 2004/40/EC [8] are as follows:

- there will be an on-going requirement to provide authoritative health and risk information to employees;
- the impact on access and working practices in most cases will be minimal, and no more than good practice would be called for case 3 of exposure;
- EMF emission testing already carried out for electrical appliances needs careful interpretation to be applied for workers' EMF exposure assessment;

- further assessment will be required if employees with pacemakers and other implanted medical devices have access to areas of elevated EMF, e.g., around induction heaters, welding devices or magnetic activators in libraries;
- access control in the vicinity of some equipment will be required; it will remain whether or not Directive 2004/40/EC is fully implemented (cases 1 and 2 of exposure) [8];
- further standardisation work (by CENELEC, European Telecommunication Standards Institute, IEC, etc.) should consider significant differences among the technical and financial requirements for EMF emission testing in laboratory conditions and EMF exposure assessment in situ.

TABLE 2. EMF Exposure at the Workplace—Common Applications Resulting in EMF Emission

	EMF Frequency Related To Application				Workers' EMF Exposure		
EMF Source	**Static**	**ELF**	**IF**	**RF/ MW**	**Probably Low-Level***	**Possibly High-Level****	**Probably High-Level*****
Induction heating		oo	o			xx	x
Surgical and physiotherapeutic use of diathermy			oo	oo		xx	x
Dielectric heating (RF: glue drying and plastic welding & MW: heating and vulcanization applications)				oo		xx	x
Arc-welding (MIG, MAG, TIG, etc.)	oo	oo	o			xx	xx
Spot welding	o	oo	o			xx	x
Electrochemical installations or other ones using microwaves (e.g., chemical activation of processes)				oo	NAD		
Electrolytic installations	o	oo			xx	x	
Industrial microwave ovens				oo	xx	x	
MRI medical diagnostic equipment	oo	oo		oo		xx	o
NMR spectrometers	oo			oo	x	x	x
Electric vehicles (trains, trams, metro)	o	o			xx	x	
Plasma discharge equipment				o	NAD		
Plasma polymerization at RF				o	NAD		
Radar and other systems				oo			xx
Broadcasting systems and devices (radio and TV: AM, VHF, UHF)		o	o	o	xx	x	x
Mobile telephony base stations				oo	xx	x	x
Military and research RF systems			o	oo	x	xx	x
RFID, EAS and other security equipment	o	o	o	o	xx	x	x
WLANs				oo	xx		
Cordless phones				o	xx		x
Bluetooth devices and hand-free kits				oo	xx		x
Electricity supplying networks and electricity distribution and transmission equipment	o				xx	x	
Electric handheld tools		o			xx	x	x
Industrial magnetizers demagnetizers	o	oo				x	

Notes. EMF—electromagnetic fields, ELF—extremely low frequency, IF—intermediate frequency, RF—radiofrequency, MW—microwave, MIG—metal inert gas, MAG—metal active gas, TIG—tungsten inert gas, NMR—nuclear magnetic resonance, MRI—magnetic resonance imaging, AM—amplitude modulation, VHF—very high frequency, UHF—ultra high frequency, RFID—radio-frequency identification, EAS—electronic article surveillance, WLAN—wireless local area network; NAD—no available data; oo—basic frequency range, which is in the most common use for specific applications; o—other frequencies, which can be used for specific applications; xx—the most common situation in the work environment; x—a possible situation in the work environment; *—detailed exposure assessment not necessary; **— assessment with external measures, using environmental measurements; ***— assessment with internal measures, computational assessment may be needed.

It is important to note that various types of workers' activities in the vicinity of particular EMF sources can result in various exposure patterns, e.g.,

- EMF emission from mobile phone base stations usually complies with the limitation of exposure for the general public, but high-level occupational exposure can occur when workers are involved in technical activities in close vicinity of the antenna of the base station.
- Radar beams usually radiate far from the locations of humans, but serious noncompliance cases of exposure may exist during manufacturing and if there is a technical dysfunction of the device.
- High-voltage power lines and transformer stations do not usually affect high-level occupational exposure, because they are switched off before technical operations. However, very high exposure to magnetic fields can occur during very specific type of work, e.g., repairing a live cable.
- An electrosurgery scalpel and supplying cables produce a high-level electric field; it can be sufficiently assessed with measurements of the exposure level of medical staff who are not in direct contact with the EMF source. However, for a surgeon holding the device, internal measures of EMF exposure should be usually considered: induced/contact currents or local thermal effects.
- A handheld activator used in libraries to re-activate (magnetise) the security strips in books produce a high 50-Hz magnetic field on the operator's hand and arm at breast level, so that measurements/ calculations of the induced current are needed for testing compliance with basic restrictions.
- The aforementioned examples indicate that there is a significant difference between testing EMF emission (which can be executed for a typical representative of each type of EMF sources) and assessing workers' EMF exposure (which should be executed for any worker, taking into account the EMF sources affecting them as well as activities which their profession duties involve). This important difference should be also presented in standardised protocols for exposure assessment.