Occupational Safety in Electric, Magnetic and Electromagnetic Fields

Proposal for an amendment of Directive 2004/40/EC

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Preface

This report analyses the concerns being raised by stakeholders, addresses weaknesses within the current text of the Directive 2004/40/EC and describes the physical and physiological basis for an effective protection of health and safety of workers with respect to occupational exposure to EMF, based on current scientific literature and studies. As a result proposals for several key issues are presented and recommendations for open questions are being made. Both can be used as a constructive input to the decision process on amending the current Directive.

Due to the ongoing technological development and scientific research, this report presents the current knowledge and possible solutions to open questions and concerns on a solid and well-established scientific foundation. As new technologies emerge and new studies and results become available or new questions and concerns are being raised, it will be updated. Therefore this report should be considered a 'living document' which tries to provide the most up-to-date source of information available for the ongoing discussion concerning occupational health and safety with regard to workers exposure to electric, magnetic and electromagnetic fields.

Contents

1 Introduction

The Directive 2004/40/EC on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (electromagnetic fields) – throughout this document to be called "The Directive" – was adopted on April 29$^{\text{th}}$, 2004 by the European Parliament and the Council of the European Union [3] requiring all member states to transpose it into national law within a timeframe of four years.

The Directive is thought to encourage '*improvements, especially in the working environment, to guarantee a better level of protection of the health and safety of workers*' without '*(. . .) imposing administrative, financial and legal constraints in a way which would hold back the creation and development of small and medium-sized undertakings*' by providing '*a system of protection against electromagnetic fields*' given by '*(...) a definition, free of excessive detail, of the objectives to be attained, the principles to be observed and the fundamental values to be applied (. . .)*'.

The exposure to EMF is limited by a set of '*exposure limit values*' given in the annex, table 1, of the Directive. Most of those values cannot be measured directly because they consist of physical quantities, e.g. current density and specific absorption rate, which exist inside the human body only.

For an indicative check whether these '*exposure limit values*' might be exceeded a second set of so called '*action values*' is given in the annex, table 2, of the Directive. Those '*action values*' are comprised of (easily) measurable external field quantities, like electric and magnetic field strength, magnetic flux density, power density, and other electrical quantities, like contact currents and limb induced currents.

If the '*action values*' are not exceeded an inherent compliance with the '*exposure limit values*' is guaranteed. However, if the '*action values*' are exceeded it does not automatically mean that the '*exposure limit values*' are exceeded. In those cases '*(. . .) the employer shall assess and, if necessary, calculate whether the exposure limit values are exceeded*'.

Other obligations of the employer, as set forth by the Directive, are to determine any exposure to electric, magnetic and electromagnetic fields (EMF) in the workplace, to assess risks related to those exposures, to take measures to reduce or avoid such risks and to inform and train workers.

Since the beginning of the decade concerns were raised by manufacturers and industries that the Directive might have an unnecessary negative impact on technological processes, equipment and workplaces. Especially users of magnet resonance imaging (MRI) equipment voiced their concerns that the Directive will impede MRI usage in patient care and research. Scientific studies [42, 48] indicated that the exposure limit values might be exceeded during normal clinical use of MRI. In the following months more and more manufacturers of equipment and users of technological processes, which uses high currents or strong magnetic fields, e.g. resistance welding, inductive heating, electrolysis, power generation, electric melting, material test systems, magnetic resonance spectroscopy, voiced their concerns that the requirements as set forth by the Directive are unduly restrictive. Especially the fact, that complex, time-consuming and therefore expensive calculations in order to show if the exposure is compliant with the '*exposure limit values*' become necessary as soon as the '*action values*' are exceeded, creates a huge burden especially for small and medium sized enterprises. Because of the choice and setting of the '*action values*' in the Directive this procedure became the norm for nearly every exposure situation and not a rare exception.

The Directive is therefore contradicting itself – see second paragraph of this chapter – due to the administrative and financial burden it creates for many employers, however, especially for small and medium sized enterprises.

Acting on those facts, the European Commission proposed a delay of the transposition of the Directive into national law for another 4 years in anticipation of a possible amendment of the Directive in order to ensure an appropriate protection of workers without having an unduly negative impact an technologies or enterprises [4]. This proposal was approved by the European Parliament and the Council on April 23$^{\text{rd}}$, 2008 [5].

This report analyses the concerns being raised by stakeholders, addresses weaknesses within the current text of the Directive and describes the physical and physiological basis for an effective protection of health and safety of workers with respect to occupational exposure to EMF based on current scientific literature and studies. As a result proposals for several key issues are presented and recommendations for open questions are being made. Both can be used as a constructive input to the decision process on amending the current Directive.

2 Methodology

The EU-Workers-Directive covers the frequency range from 0 Hz (static fields) up to 300 GHz. This report will focus on the low frequency range from 0 Hz, including static fields, up to some 100 kHz mainly. Higher frequencies will be considered only when clarifications or adjustments are necessary in order to present a complete framework with respect to occupational health and safety of workers being exposed to EMF.

A brief introductory chapter will provide information on the different physiological effects caused by EMF at different frequencies. With this knowledge *adverse effects* can be identified for each frequency range. This immediately leads to corresponding exposure limit values and other reference values, including action values. Examples of technologies or industrial processes where those exposure situations can be found or which might be impacted are provided, too.

When providing the accompanying framework, including e.g. exposure assessment, obligations of the employer, health surveillance, training of workers, documentation, the major goal is to keep things as simple as possible, reducing or avoiding any negative impact while ensuring the integrity and efficacy of the protection of the occupational health and safety of workers being exposed to EMF.

3 Physiological effects of EMF

This section gives a short description of the physiological effects associated with different kinds of fields, e.g. electric, magnetic, electromagnetic, at different frequencies, e.g. static, low-frequency, high-frequency.

Static fields, both electric and magnetic, exert forces on charges or charged particles. Static electric fields can also lead to charge separation and the charging of previously uncharged objects. Static magnetic fields can lead to strong forces on ferro- or dia-magnetic objects and can accelerate them.

The main physiological effect created by low-frequency fields is electrical stimulation of excitable body tissues, like sensory organs, nerves and muscles. This is the dominant effect in the frequency range up to some 100 kHz.

High-frequency electromagnetic fields can be absorbed by body tissues and lead to tissue heating. This effect is dominant for frequencies above several MHz.

In the transitional range between several 100 kHz and some MHz both effects prevail. The higher the frequency the more stimulation effects fade out and tissue heating effects come into play. The frequency where an effect becomes dominant and limiting depends on the characteristics of the field source. Therefore it is necessary to watch and limit both effects in this transitional frequency range.

A further distinction is made on how the EMF interacts with the human body:

- If there is a direct interaction with the body tissue, e.g. changes in ion gradients, stimulation of sensory organs, nerves and muscles, tissue heating, due to electrical field strength influenced or induced in the biological tissue by the external EMF, this type of interaction is called a *direct effect*.
- If the EMF primarily interacts with an object outside the human body, which in turn can be detrimental to health and safety of the workers, e.g. projectile risk, touch voltages and currents, this type of interaction is called an *indirect effect*.

Whenever possible, examples for workplaces, technologies or industrial processes are given, where those exposure scenarios with respect to EMF can occur.

3.1 Electric fields

The relationship between the external undisturbed electric field strength E_0 and the electric field strength in the body tissue E_i is established through the condition that the normal component of the displacement current must remain steady at the surface boundary of the human body [14, 20].

For a simple homogeneous ellipsoid model of the body it is given by:

$$E_0 \cdot k \cdot \varepsilon_0 \cdot 2\pi \cdot f = \kappa \cdot E_\mathrm{i} \tag{3.1}$$

with
- k field distortion factor; for human beings $k \approx 13 \ldots 18$
- ε_0 permittivity of free space (vacuum); $\varepsilon_0 = \frac{1}{\mu_0 \cdot c_0^2} \approx 8,854 \cdot 10^{-12} \frac{\mathrm{A}^2 \cdot \mathrm{s}^4}{\mathrm{kg} \cdot \mathrm{m}^3}$
- f frequency of the field
- κ (mean) conductivity of the body tissue(s)

In principal eqn. 3.1 remains valid even for more natural and anatomical correct body models. However, the variables k and κ become parametric functions.

3.1.1 Static electric fields

Exposure to strong static electric fields is possible whereever high DC voltages are used, e.g. high voltage direct current transmission lines and switchyards, including inverter stations.

Significant DC voltages and therefore static electric fields can be produced involuntarily by tribo-electricity, e.g. plastics production and other inductrial processes where highly insulating solids or liquids are handled and charge separation can occur [20].

The Directive contains no exposure limit values and action values for static electric fields.

3.1.1.1 Direct effects

As a immediate result of eqn. 3.1 for $f = 0$ follows: $E_\mathrm{i} = 0$, regardless of the field strength of the external static electric field. This means that the static electric field breaks down completely at the surface of the human body. The inside of the body is totally shielded from any effect of the external field. Therefore any physiological interaction with the human body – if it exists – is limited strictly to the body surface.

In very high static electric fields, exceeding $\approx 30 \frac{\mathrm{kV}}{\mathrm{m}}$, corona discharges can occur at the 'edges' of the surface of the human body, e.g. fingers, nose, ears [20, 36]. Those corona discharges can be annoying, startling or even painful depending on the field strength, posture and form of the body (field distortion) and climatic factors e.g. relative humidity.

3.1.1.2 Indirect effects

Due to influence processes electrical surface charges occur on the body surface. Because those surface charges all have the same polarity they are repelling each other and try to maintain the largest distance possible between each other. On the surface of the human body this leads to the rise of all body hair. This effect can create a mild annoyance, but is negligible, if the workers are trained and know what to expect.

An immediate impact on the health and safety of workers can occur, when a charged object is discharged through the body of the worker. Depending on the charge flowing through the workers body this could have annoying, painful or even life threatening consequences. A widely accepted limit for the discharge energy is 350 mJ [9, 32, 33, 34].

3.1.2 Low frequency electric fields

Exposure to strong low frequency electric fields is possible whereever high voltages are used, e.g. power generation and transmission, including power lines and switchyards.

3.1.2.1 Direct effects

Consulting eqn. 3.1 the relationship between the external electric field and the resulting electric field in the tissue can be rewritten as:

$$E_{\mathrm{i}} = \frac{k \cdot \varepsilon_0 \cdot 2\pi \cdot f}{\kappa} \cdot E_0 \tag{3.2}$$

Because $(k \cdot \varepsilon_0 \cdot 2\pi \cdot f) \ll \kappa$ even for the highest frequencies in the low frequency range, there still exists a large shielding effect from the outside to the inside of the human body. However, it is no longer a complete shielding as is experienced for static fields.

Especially for power frequency fields the field strength inside the body lies in the range of some $\left(\frac{\mathrm{mV}}{\mathrm{m}}\right)$ per $\left(\frac{\mathrm{kV}}{\mathrm{m}}\right)$ external electric field. With electric field strengths currently in use by technological processes (mean value $\approx 180\frac{\mathrm{kV}}{\mathrm{m}}$ for experimental high-voltage transmission lines with voltages $> 1500\mathrm{kV}$ [25]) and limited by the breakdown field strength of air ($\approx 3000\frac{\mathrm{kV}}{\mathrm{m}}$ for homogeneous fields [20, 25]), it is not possible to generate electrical fields in the tissue of the human body that can trigger any adverse physiological effect. However, it is possible that these electrical field strength in the tissue interfere with the proper operation of active medical implants, e.g. pacemakers, cardioverter defibrillators.

Very strong electric fields in excess of $\approx 30\frac{\mathrm{kV}}{\mathrm{m}}$ can cause corona discharges on the surface of the human body – see section 3.1.1.1.

3.1.2.2 Indirect effects

In principal the same effects as described in 3.1.1.2 apply, however, the charge is not constant, but instead the object is being charged and discharged with the frequency of the external electric field.

This important fact must be considered when defining safety limits. If a (momentarily) charged object is touched or grasped, there is not only a single discharge current flowing through the body, but in addition a continuous-wave (CW) charge-/discharge-current as long as the contact with the object is being maintained. The published 'safety' limits for these touch- and/or grasp-currents range from 1 - 3.5 mA (rms) for a frequency of 50 Hz up to 40 - 50 mA (rms) for frequencies in the 100 kHz and MHz range [3, 11, 26, 36, 54]. It must be noted, that the larger variation in the low frequency range is the result of a nonlinear behavior in the conductivity of the skin for small voltages and currents, so the experimental setup, execution and evaluation play a significant role. Several studies use extrapolations from other frequency ranges which remain highly questionable in the light of those non-linearities.

In general, limits for touch contacts are lower than those of grasp contacts. However, workers can be informed and trained to avoid these more annoying or even painful touch contacts or be instructed to use protective gloves.

3.2 Magnetic fields

Biological tissues are totally transparent to magnetic fields. This means that magnetic fields can penetrate the human body without being affected.

The main effect of a magnetic field is the Lorentz force $\vec{F}$ on a point charge q moving with velocity $\vec{v}$ as described by:

$$\vec{F} = q\left(\vec{v} \times \vec{B}\right) \tag{3.3}$$

Together with the Maxwell-Faraday law of induction this leads to the induction of an electrical field in a wire or another conductive medium like the human body. It is highly irrelevant if there is a movement in a constant magnetic field – perpendicular to the field lines for maximum effect – or if there is a stationary conductive body and the magnetic field penetrating it is changing over time. Spatial field gradients can enhance the induction effect.

Even if a human body is totally at rest in space, there is always movement inside the body due to e.g. heart beat, blood flow, tissue displacement due to the periodic changes in blood pressure, breathing and intestine movement. Therefore it is very difficult to separate biological effects of static magnetic fields from those of time-variant or low frequency magnetic fields in a living organism.

3.2.1 Static magnetic fields

The strongest static magnetic fields are currently used in magnet resonance imaging (MRI) and magnetic resonance spectroscopy (MRS) equipments with magnetic flux densities up to 25 T. Other sources of strong static magnetic fields are industrial processes where high DC currents are used, e.g. electrolysis.

3.2.1.1 Direct effects

A comprehensive compilation of direct effects, especially for MRI and MRS applications can be found in [29, 30, 31, 51]. However, all conclusions must be carefully examined if they really belong to direct physiological effects of static magnetic fields, because they are sometimes mixed up with effects from time-varying magnetic fields or movements in static magnetic fields.

Current data suggests possible pathological effects of static magnetic fields only for magnetic flux densities in excess of 10 T [29, 30, 31, 39, 51]. However, it must be noted, that human data is very sparse for flux densities exceeding 8 T. To make matters worse, those remaining studies are often not replicated, lack a good dosimetry or documentation and often dismiss effects as negligible for healthy volunteers without taking pathological scenarios into account.

ICNIRP [31] recommends an occupational exposure limit to static magnetic fields of 2 T for head and trunk in general and 8 T for specific work applications when the environment is controlled and appropriate work practices are in force. For a limbs only exposure a magnetic flux density of up to 14 T is deemed acceptable.

3.2.1.2 Indirect effects

Ferromagnetic materials, including so-called 'nonmagnetic stainless steel', can be very dangerous if exposed to strong static magnetic fields. Depending on their magnetic susceptibility and their shape the resulting translational forces and torques can range from negligible to lethal values. Current literature often refers to this effect as the so-called 'projectile risk' [3, 11, 31, 51]. However, the magnetic flux densities where those effects are deemed to occur differ significantly and range from 3 mT [3], 'in the order of several millitesla' [31] to 'more than 67.9 mT' [11].

Implanted devices like aneurysm clips, metal surgical clips or stents, metallic dental implants or even tattoos and permanent makeup with magnetite or iron oxide based colors can be affected by rotational or translational forces too, when being exposed to strong static magnetic fields with sometimes life threatening consequences.

In order to get a solid basis for any exposure limit values a quantitative view on this effect is presented in section 3.2.1.3.

Another important indirect effect of static magnetic fields is the possible operational interference with implanted devices, e.g. pacemakers, cardioverter defibrillators, for magnetic flux densities of more than $0.5 \ldots 0.8$ mT.

3.2.1.3 Projectile risk

A quantitative solution for the translational and rotational forces on a ferromagnetic object being placed in a static magnetic field can be obtained by solving Maxwell's equations for static magnetic fields in a carthesian coordinate system [14]. By restricting the shape of the ferromagnetic object from a general ellipsoid to a rotational symmetrical ellipsoid object and further to the shape of a sphere, the number of independent principal axis can be reduced from three to one. Further simplifications can be reached by placing the ferromagnetic sphere in the static magnetic field at points located along the central axis of a cylindrical (superconducting) magnet. The unit vectors $\vec{e_{\mathrm{x}}}$, $\vec{e_{\mathrm{y}}}$ and $\vec{e_{\mathrm{z}}}$ form a right-handed coordinate system, with $\vec{e_{\mathrm{z}}}$ pointing to the inside of the magnet and the origin of the coordinate system being placed on the central axis of the magnet.

As is true for magnets commonly used in MRI, the only non-zero spatial magnetic component at a location with coordinates $x = 0$ and $y = 0$ is B_{z}.

The translational force on a ferromagnetic sphere is given by:

$$F_{\mathrm{z}} \approx \frac{3V}{\mu_0} \cdot B_{\mathrm{z}} \frac{\partial B_{\mathrm{z}}}{\partial z} \tag{3.4}$$

with V being the volume of the sphere
μ_0 permeability of free space; $\mu_0 = 4\pi \cdot 10^{-7} \frac{\mathrm{N}}{\mathrm{A}^2} = 4\pi \cdot 10^{-7} \frac{\mathrm{T \cdot m}}{\mathrm{A}} \approx 1.2566 \cdot 10^{-6} \frac{\mathrm{H}}{\mathrm{m}}$

According to eqn. 3.4 a translational force on the ferromagnetic sphere exists only, if the magnetic flux density-spatial gradient-product $B_{\mathrm{z}} \frac{\partial B_{\mathrm{z}}}{\partial z}$ if different from zero. This means, that far away from the magnet ($B_{\mathrm{z}} \to 0$ and $\frac{\partial B_{\mathrm{z}}}{\partial z} \to 0$) and in the homogeneous region of the field ($\frac{\partial B_{\mathrm{z}}}{\partial z} \to 0$), usually inside the magnet, no translational force exists and therefore no so called projectile risk could occur. The maximum translational force is to be expected near the opening to the bore for most magnets, where the product $B_{\mathrm{z}} \frac{\partial B_{\mathrm{z}}}{\partial z}$ reaches its maximum.

In order for the sphere to be accelerated it is necessary to overcome at least the sliding friction force F_{sf}:

$$F_{\mathrm{z}} \stackrel{!}{=} F_{\mathrm{sf}} \tag{3.5}$$

F_{sf} can be calculated as:

$$F_{\mathrm{sf}} = \mu_{\mathrm{sf}} \cdot \delta \cdot V \cdot g \tag{3.6}$$

with μ_{sf} sliding friction coefficient; for steel on steel $\mu_{\mathrm{sf}} = 0.06$
δ mass density; for steel $\delta \approx 8000 \frac{\mathrm{kg}}{\mathrm{m}^3}$
g standard gravity; at sea-level $g = 9.80665 \frac{\mathrm{N}}{\mathrm{kg}}$

Solving

$$\frac{3V}{\mu_0} \cdot B_{\mathrm{z}} \frac{\partial B_{\mathrm{z}}}{\partial z} = \mu_{\mathrm{sf}} \cdot \delta \cdot V \cdot g \tag{3.7}$$

for the magnetic field parameters $B_{\mathrm{z}} \frac{\partial B_{\mathrm{z}}}{\partial z}$, the result becomes independent of the volume V of the sphere and the exact magnetic quantities of its material, as long as it is a ferromagnetic substance with a magnetic volume susceptibility $\chi_{\mathrm{mv}} \gg 1$:

$$B_{\mathrm{z}} \frac{\partial B_{\mathrm{z}}}{\partial z} = \mu_{\mathrm{sf}} \cdot \delta \cdot g \cdot \frac{\mu_0}{3} \tag{3.8}$$

For non-magnetic materials $\chi_{\mathrm{mv}} \ll 1$ the result is still independent of the volume V of the sphere but depends on the exact magnetic quantities of the material of the sphere:

$$B_{\mathrm{z}} \frac{\partial B_{\mathrm{z}}}{\partial z} = \mu_{\mathrm{sf}} \cdot \delta \cdot g \cdot \frac{\mu_0}{\chi_{\mathrm{mv}}} \tag{3.9}$$

As given by eqn. 3.9 so called 'non-magnetic' materials require a much higher magnetic flux density-spatial gradient-product than ferromagnetics, in order to overcome the initial friction force. So, for a worst case assumption it is safe to focus on ferromagnetic materials with a high susceptibility value.

Eqn. 3.8 gives for a ferromagnetic steel sphere:

$$B_{\mathrm{z}} \frac{\partial B_{\mathrm{z}}}{\partial z} \approx 2 \cdot 10^{-3} \frac{\mathrm{T}^2}{\mathrm{m}} \tag{3.10}$$

Most unshielded superconducting cylindrical magnets used in MRI, independent of their absolute magnetic field strength, have a ratio $\max\left(B_{\mathrm{z}}^2\right) / \max\left(\frac{\partial B_{\mathrm{z}}}{\partial z}\right)$ in the range of $1.8 \ldots 2\ \mathrm{m}^{-1}$ [24, 50].

This magnetic field characteristic (spatial magnetic gradient) together with eqn. 3.10 gives a minimum magnetic flux density $B_{\mathrm{z}} \approx 60\mathrm{mT}$ needed to overcome the initial frictional force, which in turn makes it possible that the sphere is accelerated in the magnetic field and a so called '*projectile risk*' can occur. This result is in good agreement with the value given in [11].

In general, shielded magnets have a smaller ratio $\max\left(B_{\mathrm{z}}^2\right) / \max\left(\frac{\partial B_{\mathrm{z}}}{\partial z}\right)$ than unshielded magnets. Because of the higher spatial gradients this leads to a lower minimum magnetic flux density which could constitute a so called '*projectile risk*'. Current data for shielded systems suggests a minimum magnetic flux densities in the central axis of a superconducting cylindrical magnet in the range from $30 \ldots 40$ mT necessary for a projectile risk to occur.

For non-spherical objects not only a translational force can exist, but a torque as well. Needle-shaped rotational ellipsoids try to turn their long axis parallel to the direction of the field. The magnitude of the torque is proportional to B_{z}^2, so the maximum torque is to be expected in the center of the magnet and can be much higher than the maximum translational force.

3.2.2 Low frequency magnetic fields

Low frequency magnetic fields are ubiquitous at workplaces where electric energy is used. The exposure to low frequency magnetic fields at workplaces ranges in terms of magnetic flux density from some nano- or microtesla, e.g. office buildings, up to several tenth or hundreds of millitesla, e.g. power generation, electric melting, resistance welding, inductive heating, and in terms of frequency from fractions of 1 Hz, e.g. movement in static fields, up to some tenth or hundreds of kHz, e.g. inductive heating.

3.2.2.1 Direct effects

A comprehensive compilation of direct physiological effects of low frequency magnetic fields can be found in [26, 29, 30, 36, 38, 41, 43, 44, 45, 54].

The main physiological effect created by low-frequency magnetic fields is electrical stimulation of excitable body tissues, like sensory organs, nerves and muscles. Because different excitable body tissues have different maximum sensitivities with respect to the frequency, the major points of interaction change with the frequency:

Maximum sensitivity	Physiological effect	Point of interaction
$\ll 1$ Hz	Metallic taste	Receptors in the tongue (shift in ion gradients)
$< 0.1 \ldots 2$ Hz	Vertigo, nausea Blood flow induced EMF	Inner ear (vestibular system) Nerve, muscle excitation (interference with heart action)
≈ 20 Hz	Magnetophosphenes	Retina
≈ 50 Hz	Tactile and pain sensations Loss of muscle control Interference with heart action	Peripheral nerves Peripheral nerves, muscles Heart

Extremely low frequency sensory effects caused by movements in a strong static magnetic field are experienced with flux densities above 2 - 3 T [12, 19, 31]. The maximum sensitivity is expected at frequencies around 0.1 Hz. These effects sometimes last longer than the actual field exposure and can, in single cases, be detrimental to work performance and quality.

Pathological effects of blood flow induced EMF causing nerve and muscle excitation in the immediate vicinity of the blood vessels or that may interfere with the heart action are expected for flux densities in excess of 8 - 10 T [51].

Magnetophosphenes have a very sharp response peak (maximum sensitivity) at 20 Hz. For lower frequencies the sensitivity decreases approximately proportional with f, for higher frequencies the decrease in sensitivity is proportional to nearly f^3. Therefore magnetic flux densities necessary to evoke magnetophosphenes vary significantly with the frequency and are to be expected at workplaces where the head can be in close proximity to high current conductors, e.g. resistance welding. Phosphenes can be nothing more than irritating, but also occur in ones daily life's when rubbing the eyes or when sneezing.

The maximum sensitivity for nerve and muscle stimulation is at 50 Hz. However, the response curve is very flat in the frequency range of 10 Hz to some hundreds of Hz. Only for frequencies lower than 4 - 5 Hz or higher than 3 - 5 kHz the sensitivity decreases approximately proportional with f. In general, the thresholds for the direct stimulation of muscles are much higher than for nervous structures, the latter therefore becoming the limiting ones. However, these stimulation effects only occur at field strength well above those used in most industrial processes, excluding special MRI applications.

All these physiological effects have a clearly defined threshold. Any stimuli below the threshold value will not cause a physiological response, even when applied for a long time.

3.2.2.2 Indirect effects

For low frequency magnetic fields with frequencies up to some 100 Hz in general the same indirect effects as described in section 3.2.1.2 apply. However, especially the rotational or torque forces play a greater role for time-varying magnetic fields than any translational forces. Magnetic fields with frequencies in the range of some tenth or hundreds of kHz can heat up implanted conductive objects.

Because of the induced electrical field strength in the tissue and in the circuits of implanted electronic devices the correct operation of those devices can be negatively influenced. The possible interference effect of low frequency magnetic fields with implanted devices is dependend on frequency and other field characteristics.

Voltages and currents induced in conductive structures in the field can generate touch voltages and currents which need to be limited. In general, the same limits as described in section 3.1.2.2 apply.

3.3 High frequency electromagnetic fields

Based on physiological effects high frequency (HF) electromagnetic fields cover the frequency range from several 100 kHz to 300 GHz. Technological processes using high frequency electromagnetic fields can be found e.g. in broadcast and communications applications, inductive and dielectric heating, HF-dryers and medical applications, like diathermie and MRI.

3.3.1 Direct effects

If the electromagnetic energy is absorbed in the biological tissue this leads to an increase in tissue temperature. The temperature increase must be limited in order to prevent adverse biological effects. A commonly used value is to limit the temperature increase in the tissue caused by an external electromagnetic field to a maximum value of 1 ℃ [26, 52]. Experimental data links an exposure of resting humans for approximately 30 minutes to high frequency electromagnetic fields producing a whole-body specific absorption rate (SAR) of 1 − 4 W/kg to an increase in body temperature of less than 1 ℃ [26, 52]. In order to take into account additional effects such as high ambient temperature and humidity together with an increased level of physical activity the limit value for whole-body SAR is set to 0.4 W/kg for occupational exposures in the frequency range between 100 kHz up to 10 GHz [26]. For localized exposures to high frequency electromagnetic fields higher SAR values are permissible because of heat dissipation and active thermoregulation. ICNIRP [26] gives SAR values of 10 W/kg for a localized exposure of head and trunk and 20W/kg for a localized exposure of the limbs in the frequency range between 100 kHz up to 10 GHz. Identical values can be found in the Directive [3].

The penetration depth into the biological tissue for electromagnetic energy is both frequency- and tissue-dependend. The higher both the frequency of the electromagnetic field and the electrical permittivity of the biological tissue, e.g. the water content of the tissue, the shorter the penetration depth. For frequencies exceeding 10 GHz the penetration depth in biological tissue is very shallow which makes the SAR concept, with its volumetric model of heat production, an inadequate metric to ensure safety. In oder to prevent excessive tissue heating at or near the body surface, the power density is the limiting factor for exposures to EMF in the frequency range between 10 GHz and 300 GHz. Both ICNIRP [26] and the Directive [3] give identical values of $50\mathrm{W/m^2}$ for the power density and occupational exposure.

3.3.2 Indirect effects

Conductive structures in a high frequency electromagnetic field can act as an antenna and can lead to shocks and burns when touched or grasped. Depending on frequency and field strength and due to the capacitive coupling mechanisms severe burns can occur even before a direct touch or grasp contact is established. Therefore the use of 'normal' gloves as a protective measure is not recommended in the high frequency range. Exposure limit values for touch currents are given in section 3.1.2.2 and [3, 11, 26, 36, 52].

4 Limiting occupational exposure to static and low frequency electric and magnetic fields

4.1 Level of protection

The preamble of the Directive states: '*It is now considered necessary to introduce measures protecting workers from the risks associated with electromagnetic fields, owing to their effects on the health and safety of workers.*' It also states: '*This Directive lays down minimum requirements, thus giving Member States the option of maintaining or adopting more favorable provisions for the protection of workers, in particular the fixing of lower values for the action values or the exposure limit values for electromagnetic fields.*

The major goal of the Directive is therefore the protection of the health and safety of workers. This means, that any physiological effects caused by an exposure to EMF must be limited in such a way, that they are neither detrimental to the health of the worker nor compromise the safety of the worker. All physiological effects listed in section 3 must be evaluated if they pose a potential threat to the health and safety of workers being exposed to EMF.

Any

- interference with heart action
- loss of muscle control
- painful or annoying sensations
- severe form of vertigo and nausea

- whole-body heat stress and excessive localized tissue heating

immediately qualifies as a potential threat to the health and safety of workers and must therefore be avoided by limiting the exposure to EMF accordingly.

Other effects, like phosphenes, may or may not pose a potential safety threat, depending on the working environment and the duty of the worker.

Effects like

- metallic taste
- minor tactile sensations at threshold level

are felt to be no immediate threat to the health and safety of workers, but should be minimized as far as possible.

The proposed exposure limit values, action values and additional reference values presented in section 5 are based on this valuation.

4.2 Revisiting problems with the current Directive

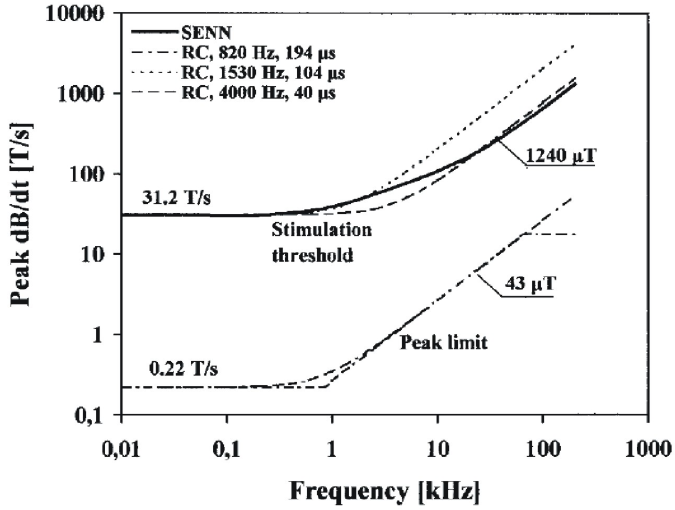

Figure 4.1: Stimulation threshold and peak limit for a sinusoidal magnetic field as a function of frequency (Jokela 2000 [37]). The solid curve shows the stimulation threshold calculated with the SENN (spatially extended nonlinear nodal) model of (Reilly 1998 [44]). The lower curve is the peak limit for occupational exposures. Taken from [28].

Some of the problems with the current Directive have already been described in the sections 1 and 3. Especially the need for complex, time-consuming and therefore expensive calculations in order to show if the exposure is compliant with the '*exposure limit values*' as soon as the '*action values*' are exceeded, creates a huge burden especially for small and medium sized enterprises. Because of the choice and setting of the '*action values*' in the Directive this procedure is the norm for nearly every exposure situation and not a rare exception.

ICNIRP states in [26] '*(...) it was decided that, for frequencies in the range 4 Hz to 1 kHz, occupational exposure should be limited to fields that induce current densities less than* 10mA/m^2, *i.e., to use a safety factor of 10*'. However, fig. 3 of the ICNIRP document [28] – reproduced here as fig. 4.1 – gives a peak limit $\mathrm{d}B/\mathrm{d}t$-value for occupational exposure of 0.22 T/s, which, when compared to the peak $\mathrm{d}B/\mathrm{d}t$-value for the threshold of peripheral nerve stimulation (PNS) of 31.2 T/s also given in this figure, reveals a 'safety factor' of 100 and more [21].

The most important problem to be solved, is to establish exposure limit values which ensure a sound level of protection, as described in section 4.1, without creating the need for unnecessary measures, which do not improve workers safety in EMF at all.

Another important problem is the proper choice and setting of the '*action values*' which serve as an indicator when one or more of the actions and measures specified in the Directive must be undertaken. With the current settings of these action values they are exceeded in many workplaces and therefore require further assessment in order to show wether or not the exposure limit values are exceeded.

Other problems needed to be addressed are:

- Non-sinusoidal, pulsed or intermittent exposures
- Exposure to multiple sources or multiple frequencies
- An easy to use procedure to show compliance with the exposure limit values, if the action values are exceeded

4.3 Exposure assessment

The assumption that exposure assessment always means measurement or calculation of EMFs is a common misunderstanding.

The whole exposure assessment process consists of several important steps:

- Inventory of equipment in the workplace
- Identify characteristics of the equipment with respect to EMF, e.g. frequency, emitted power, duty factor, ...
- Conditions of use of the equipment, e.g. normal position of operator, position of workers other than the operator, time spent at normal position, operations or maintenance or repair at distances from the emitting equipment closer than those recommended in the manufacturers instructions, situations of foreseeable incidents, and situations of foreseeable misuse, ...
- Determine EMFs at worker/operator positions
- Compare determined levels of EMFs to action values and/or exposure limit values

It is important to note, that not all steps outlined above need to be performed for all types of equipment.

For instance, if the workplace contains only non-electrical equipment or electrical equipment which either does not produce EMFs or produces them at levels below the action values or even below the general public exposure limits, no further steps or assessment are necessary. Examples for these types of equipment can be found in table 1 and 2 in [8] and table 1 in [10].

Both [8, 10] also contain tables with examples of equipment where a complete exposure assessment is likely to be necessary or even mandatory.

Only then it is necessary, to gather further information on the equipment, its use and to determine the levels of EMFs at workers/operators position. '*Determine*' means that, e.g. information from the manufacturer, comparison with similar workplaces, containing similar equipment used in a similar way, measurement or calculation procedures can be used. It does <u>not</u> mean, that measurements or calculations are mandatory in any way.

In terms of costs measurement and calculation procedures which test direct compliance with the exposure limit values are the most expensive ones and require a high degree of expertise and often highly specialized equipment. Calculations of electric, magnetic and electromagnetic field quantities are much cheaper but also require a high degree of expertise and often special hardware. In many cases the cheapest and most versatile solution is to perform measurements of the electric, magnetic and electromagnetic field quantities directly in the workplace. However, this is necessary only, if other ways to determine workers exposure to EMF give no satisfactory or conclusive results.

5 Proposal for limiting occupational exposure to static and low frequency electric and magnetic fields

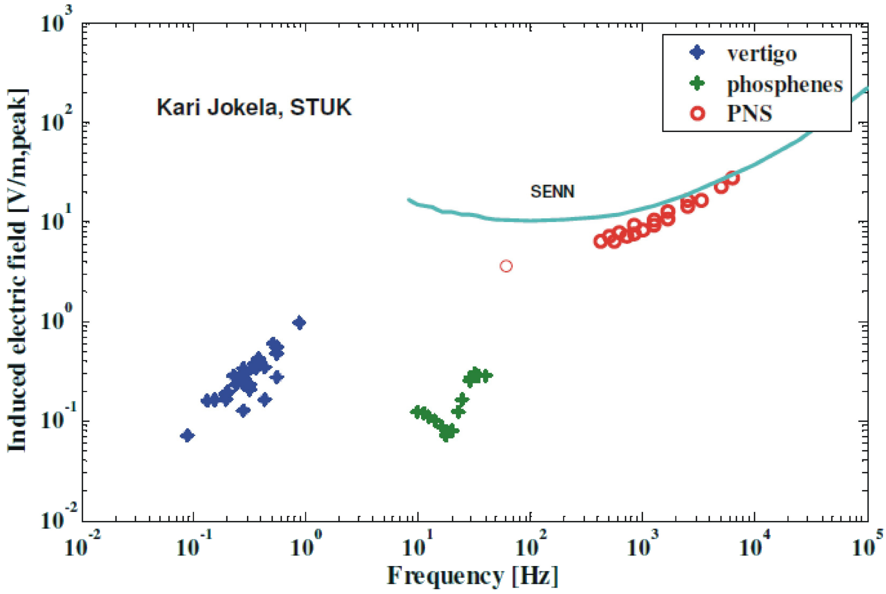

Figure 5.1: Thresholds for vertigo, phosphenes and peripheral nerve stimulation. Taken from [40, 49].

In recent presentations [40, 49] the thresholds for the onset of vertigo, phosphenes and peripheral nerve stimulation, as reported in several laboratory volunteer studies, were summarized and compared to a SENN model calculation. This diagram is reproduced here as fig. 5.1.

Fig. 5.1 reveals a large difference between the SENN model calculations and the onset of peripheral nerve stimulation, especially in the frequency range between 50 Hz and several 100 Hz. The SENN model does not take into account the complex behavior of the voltage-gated ion channels responsible for the generation of an action potential. Those channels are not only on-/off-switches but have several internal states and additional requirements which must be met before a state change could occur [23]. Because the IEEE standard [36] is largely depending on the SENN model and accompanying literature [43, 44] the exposure limit values stated there must be carefully reevaluated, as is true for all studies used to make up fig. 5.1.[1]

As stated before, the main focus of this report is on the low frequency range, including static fields. Therefore the results of this investigation are presented for this frequency range only, leaving the high frequency range unchanged for the moment. It must be noted, that minor changes, not to the exposure limit values themselves, but to the footnotes and the text given in the current Directive, as well as the action values, might become necessary at a later stage.

5.1 Exposure limit values

The fundamental metric to quantify physiological effects based on electrical stimulation of excitable body tissue is the electric field strength in the tissue. Because these effects are threshold based the maximum or peak value of the electric field strength in the tissue is the relevant parameter which needs to be limited. If this peak tissue field strength remains below the stimulation threshold at all times, no stimulation will occur [21, 22, 23, 36, 40, 43, 44, 49].

This seems to be a paradigm shift when compared to the current Directive, underlying guidelines [26, 27] or comparable standards [36], where sometimes current densities in the tissue, but always

[1] All datapoints shown in fig. 5.1 and all underlying studies are currently under reevaluation and are checked for validity and accuracy.

root-mean-square (rms) values are used. However, rms-values are a very poor metric for limiting stimulation effects, especially in the case of exposures to non-sinusoidal, pulsed or intermittend EMF [21, 22]. Using peak values not only addresses many open issues listed in section 4.2 but also makes exposure assessment much easier.

When it comes to address tissue heating effects in the high frequency range, rms-values are still the correct and most relevant exposure limiting metric, even for non-sinusoidal, pulsed or intermittend EMF.

Therefore it is necessary to give both peak and rms-values in order to address the different physiological effects, e.g. stimulation and tissue heating, in the low and high frequency range, respectively.

5.1.1 Static electric fields

The exposure limit values for static electric fields are given in table 5.1.

As stated in section 3.1.1.1 the external static electric field cannot penetrate the body surface. Therefore the exposure limit values are solely based on indirect effects of the static electric field and are given as direct measureable external field quantities.

Electric field strength [(a)] [kV/m]	Maximum discharge energy [(b)] [mJ]
30	350

Note: (a) Value refers to the spatial maximum
(b) Applicable only if the worker can touch a charged object

Table 5.1: Exposure limit values for static electric fields

5.1.2 Static magnetic fields

The exposure limit values for static magnetic fields are given in table 5.2.

Sections 3.2.1, 3.2.1.2 and 3.2.1.3 give the rationale for setting these exposure limit values stated as directly measureable external field quantities.

Maximum magnetic flux density	
Exposure of head and trunk [(a,b,c)] [T]	Exposure of limbs only [(a,b)] [T]
2	14

Note: (a) Value refers to the spatial maximum
(b) Magnetic flux densities in excess of 30 mT are allowed, if any projectile risk or any risk from translational or rotational forces on metallic objects or implants can be excluded
(c) For controlled environments where access is limited to specially informed and trained workers, where special work practices and measures are in force and where a detailed risk analysis shows that any risks to the health and safety of the workers or any negative impact on their duties or the safety of others with regard to vertigo, nausea and phosphenes can be excluded, magnetic flux densities up to 8 T are allowed

Table 5.2: Exposure limit values for static magnetic fields

5.1.3 Low frequency electric and magnetic fields

With regard to fig. 5.1, the valuation in section 4.1, the results from section 3 and the accompanying literature it is possible to establish exposure limit values which address all direct adverse effects

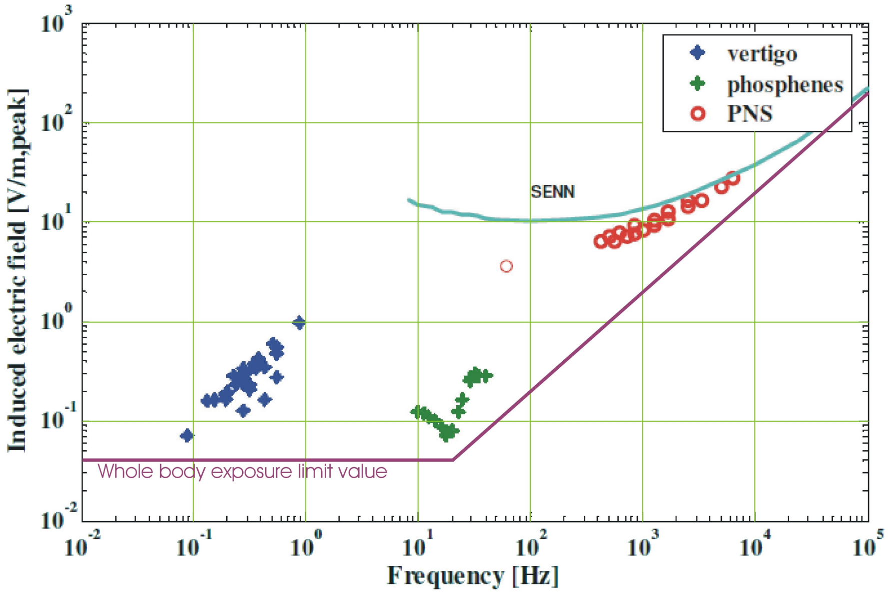

Figure 5.2: Exposure limit values to electric and magnetic fields for whole body exposures

based on electrical stimulation. These whole body exposure limit values are given in fig. 5.2. They also apply for partial body exposures of the head only, because this is the main area of interaction for effects like vertigo, nausea and (magneto-)phosphenes.

For partial body exposures of the trunk of the human body only and for controlled environments, where access is limited to specially informed and trained workers, where special work practices and measures are in force and where a detailed risk analysis shows that any risks to the health and safety of the workers or any negative impact on their duties or the safety of others, with regard to vertigo, nausea and phosphenes can be excluded, the use of the exposure limit values shown in fig. 5.3 are allowed. However, due to the possibility that slightly annoying indirect effects might occur more frequently, the use of these exposure limit values should be restricted to fractions of a whole work shift.

The exposure limit values for time varying, low frequency electric and magnetic fields are summarized in table 5.3 and given as peak electric field strength in the tissue.

Fig. 5.4 shows a comparison of the basic restrictions or exposure limit values for time-varying EMF given in the ICNIRP guidelines [26] or the identical values in the Directive [3] and the IEEE standard C95.6 [36] together with data given in section 5.1.3 of this report.

The curves 'IEEE brain' and 'IEEE other' represent the basic restrictions for occupational exposure as given in [36].

Exposure limit values given as current densities, e.g. ICNIRP guidelines [26] or the identical exposure limit values of the Directive [3], were converted to peak electric field strength in the tissue – curve 'ICNIRP' – by using the frequency dependent dielectric properties of the body tissues database established by C. Gabriel et. al. [15, 16, 17, 18]. Because of the frequency dependent dielectric properties of the body tissues the part of the curve for frequencies exceeding 1 kHz is not a straight line or has a constant frequency dependency. The same is true for frequencies between 10 Hz and 1 kHz, but the changes are more subtle and can therefore be approximated by a straight line. Because no dielectric tissue data is available for frequencies below 10 Hz, the values for the dielectric tissue properties given for a frequency of 10 Hz are also used for all smaller frequencies.

The curves 'Whole body/Head only' and 'Trunk only/Controlled environment' represent the data given in table 5.3.

Curve 'ICNIRP SAR' represents the frequency dependent electric field strength limit in the tissue

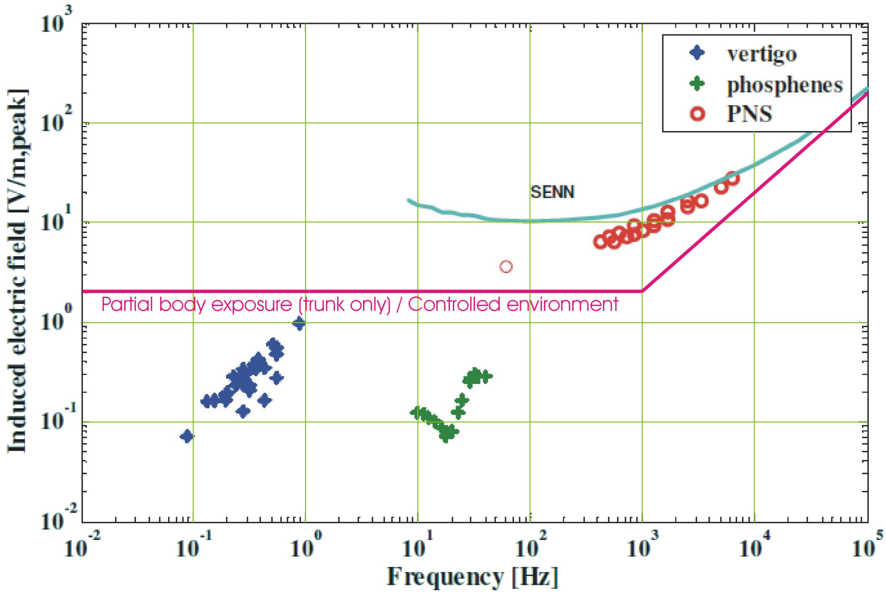

Figure 5.3: Exposure limit values to electric and magnetic fields for partial body exposures (trunk only) and controlled work environments

	Peak electric field strength in the tissue	
Frequency range	Whole body exposure [(a,b,d)] or head only exposure [(a,b,d)]	Trunk only exposure [(a,b,c,d)]
f / Hz	[V/m]	[V/m]
$0 < f \leq 20$	0.04	2
$20 < f \leq 1000$	$f/500$	2
$10^3 < f \leq 10^6$	$f/500$	$f/500$

Note:
(a) Value refers to the spatial maximum
(b) Value given is the peak permissible electric field strength in the tissue and must not be exceeded. Uncertainties coupled with measurement or calculation procedures must be subtracted.
(c) For controlled environments where access is limited to specially informed and trained workers, where special work practices and measures are in force and where a detailed risk analysis shows that any risks to the health and safety of the workers or any negative impact on their duties or the safety of others with regard to vertigo, nausea and phosphenes can be excluded, this value also applies to whole body exposures
(d) Peak electric field strength in the tissue exceeding 25 V/m must also be checked for compliance with the exposure limit values for whole- and partial-body SAR

Table 5.3: Exposure limit values for low frequency electric and magnetic fields

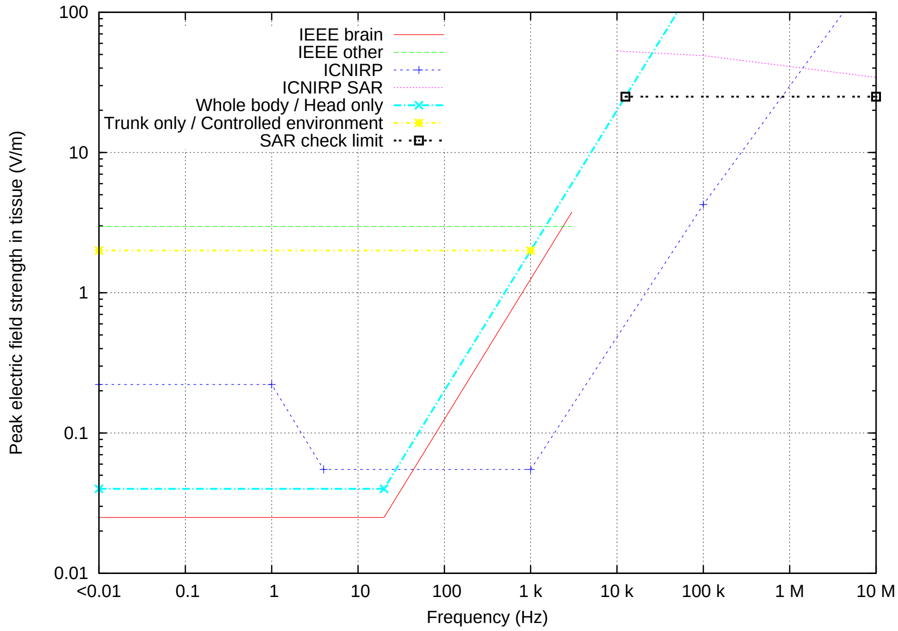

Figure 5.4: Comparison of basic restrictions for time-varying EMF given in ICNIRP guidelines and IEEE standard C95.6 with data given in this report

where the whole-body SAR of 0.4 W/kg is reached for a continuous-wave EMF. Because of the frequency dependent dielectric properties of body tissues this is not a straight line or has a constant frequency dependency and therefore requires some effort to calculate.

In order to simplify the exposure assessment for the user, an indicative value – see table 5.3, note (d) – for the peak electric field strength in the tissue is given as curve 'SAR check limit'. If the peak electric field strength in the tissue does exceed this value, a compliance check with the exposure limit values for whole- and partial-body SAR should be performed. However, if this value is not exceeded, it is also certain, even for worst-case exposure scenarios, that the whole- and partial-body SAR exposure limit values will not be exceeded, making an additional compliance check unnecessary.

5.1.4 High frequency electromagnetic fields

Because this report has a focus on static and low frequency electric and magnetic fields, the exposure limit values for high frequency electromagnetic fields remain unchanged for the moment. Therefore the exposure limit values given in the last three columns of table 1 of the Directive [3], together with all corresponding notes, will not be changed. Additional information on adverse direct and indirect effects of an occupational exposure to high frequency electromagnetic fields and the rationale for these exposure limit values is given in section 3.3.

5.2 Reference and action values

The metrics, e.g. basic restrictions and exposure limit values, that best describe the onset of adverse physiological reactions are mainly quantities that only exist in the biological tissue, e.g. peak electric field strength in the tissue for stimulation effects and SAR for tissue heating, and are therefore not directly measureable. EMFs are the only physical agents where this problem exists and therefore require a special solution.

By using body models with different resolution and complexity it is possible to establish a link between the body-internal exposure-limiting quantities, e.g. peak electric field strength in the tissue and SAR, and directly measureable external field quantities for a given exposure situation.

Because the relationship between internal and external physical quantities is influenced by many parameters, e.g. frequency, distance, field source, exposure situation, posture, . . . , it is not possible to give a single number which represents an exact exposure assessment for all cases. However, it is possible to give a single number for each frequency, which might introduce a small overestimation of the exposure under some conditions, but guarantees, even assuming worst-case exposure scenarios, that the basic restrictions or exposure limit values will not be exceeded. These values are called '*Reference values*' and are given to simplify exposure assessment, because they need to be established only once and can furtheron be used for the assessment of every exposure scenario.

Reference values are easily measureable external field quantities, e.g. electric field strength, magnetic flux density, contact currents and discharge energies. Compliance with these reference values ensures compliance with the exposure limit values. The reference values may be exceeded as long as there is compliance with the exposure limit values.

'*Action values*' are a special set of reference values. If the action values are not exceeded no further actions or measures as specified in the Directive are necessary. Exceptions to this rule are listed in article 4, paragraph 5 of the Directive [3].

5.2.1 Reference values

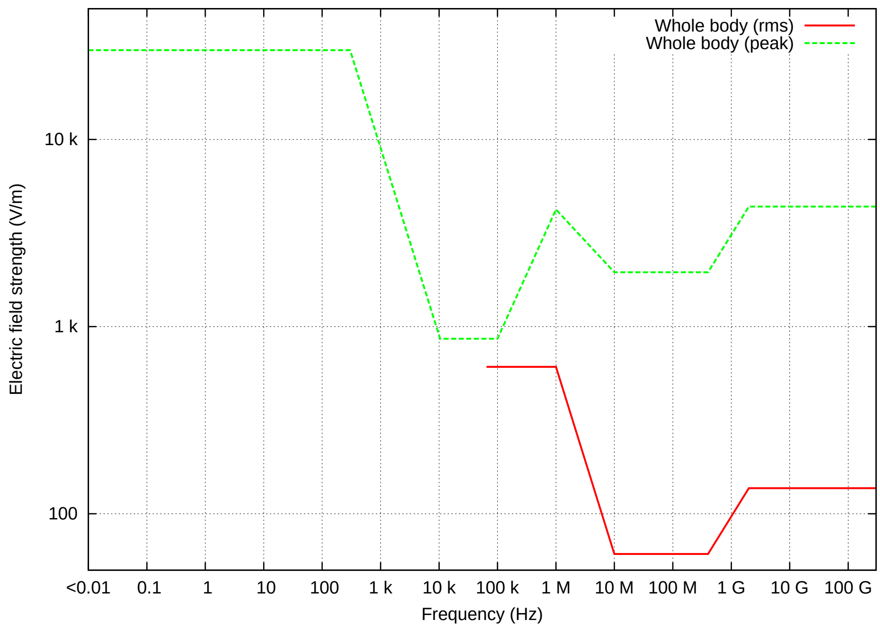

Figure 5.5: Reference values for occupational exposure to electric fields

In order to simplify the determination of workers exposure to EMF as outlined above, it is necessary to transform the not directly measureable body-internal exposure limit values in a set of directly measureable external physical field quantities.

Fig. 5.5 and 5.6 show the reference values for the electric field strength and magnetic flux density for the exposure limit values given in table 5.3. However, it has to be noted, that the reference values shown in both fig. 5.5 and 5.6 are mostely based on direct effects and therefore limitations caused by indirect effects are largely excluded.

The reference values in the high frequency range ($f > 100$kHz) are reproduced unchanged from the Directive and shown for completeness only.

The reference values for static and low frequency electric and magnetic fields were derived from the exposure limit values shown in table 5.3 by taking into account that the exposure limit values will

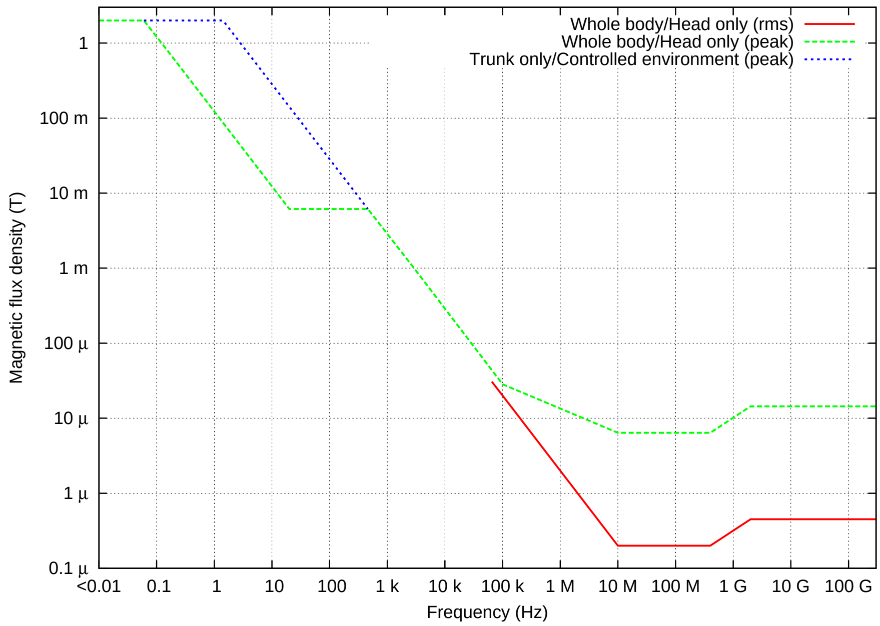

Figure 5.6: Reference values for occupational exposure to magnetic fields

not be exceeded, even assuming worst-case exposure scenarios, and that the new curve matches the reference values given by the Directive at a frequency of 100 kHz.

It must be noted, that especially in the frequency range between 100 kHz and 10 MHz the reference values given in the Directive are mostely relying on extrapolation and curve fitting and lack a solid scientific and physiological basis. However, the approach is a (over-)conservative one and can therefore be used for the time being.

For frequencies below 65 kHz the reference values are given as peak values of the electric field strength or the magnetic flux density, because the peak value is the physiological relevant metric. For frequencies above 65 kHz both peak and rms values are given. Depending on the behavior of the EMF source, e.g. CW or pulsed, the limiting value may be either the rms or the peak value. However, in most cases it is sufficient to show compliance with the rms values given.

Because the Directive does only specify '*the minimum health and safety requirements*' this single set of reference values in order to simplify exposure assessment by providing directly measureable field quantities might be sufficient. However, it will simplify exposure assessment and the necessity of actions and measures even more, if these actions and measures are coupled to other sets of reference values. Doing this, will allow for a graded response with actions and measures, e.g. general information, signage, access control, special training, for increasing exposures at the workplace. This approach will reduce the overall cost for actions and measures even further, because the full spectrum of actions and measures is needed only at workplaces with a high level of exposure to EMF.

5.2.2 Action values

If the action values are not exceeded no further actions or measures as specified in the Directive are necessary. It is therefore an intriguing notion to set the action values as high as possible, while still ensuring compliance with the relevant exposure limit values, in order to minimize any obligations to actions or measures, thus saving costs.

However, this is an ill-fated attempt from the beginning, because the Directive explicitely requires the employer to give particular attention to any indirect effects arising from exposures to EMF. At the same time the gap between the reference levels for the general public [2] and the action values for

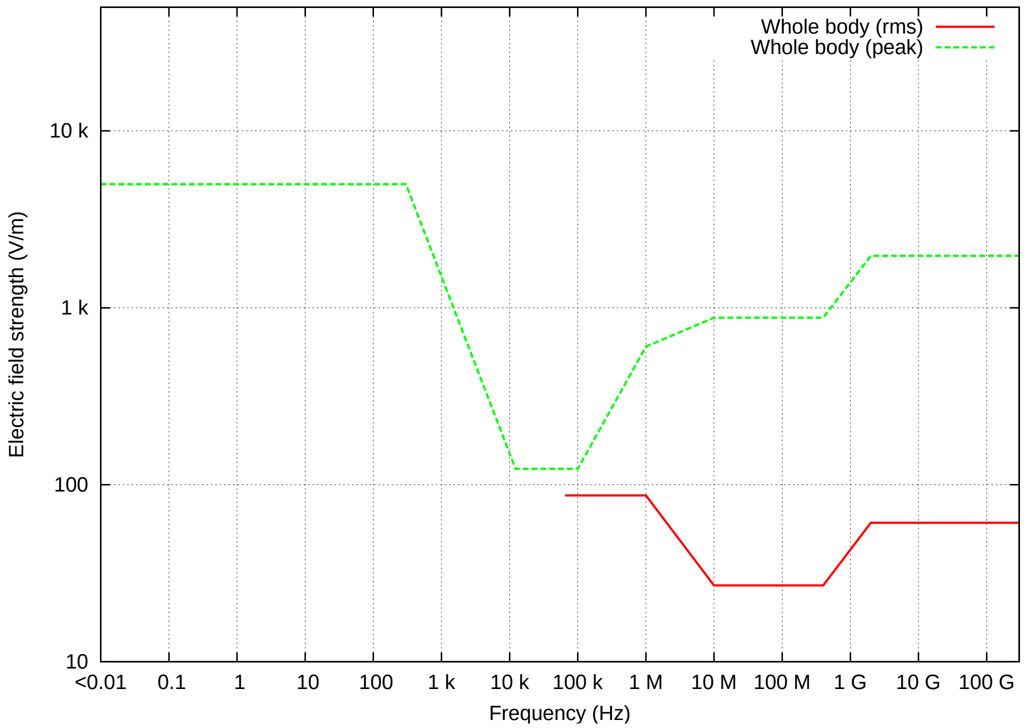

Figure 5.7: Action values for occupational exposure to electric fields

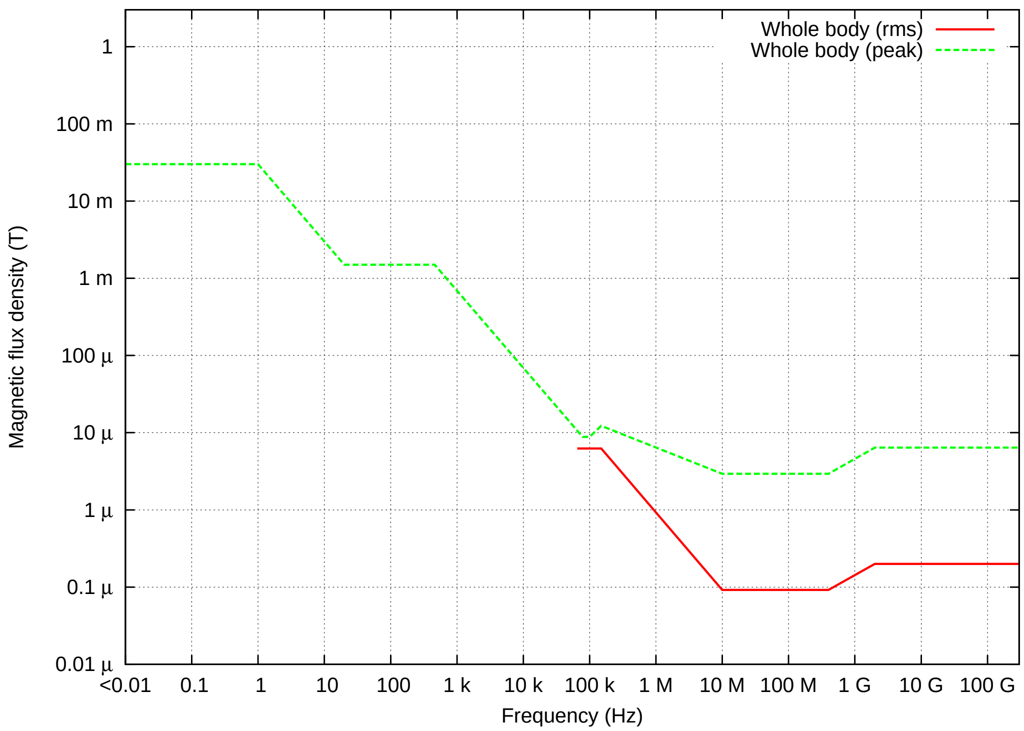

Figure 5.8: Action values for occupational exposure to magnetic fields

occupational exposure should not become too large in order to avoid acceptance problems. Because babies, children, elderly people and severely ill persons are not part of the active workforce, it is possible to justify higher exposures to EMF for workers, but only to a certain extend.

Taking this into account and modifying the set of reference values given in fig. 5.5 and 5.6 yields for the results shown in fig. 5.7 and 5.8. In the high frequency range ($f > 100$kHz) the action values are identical with the reference values for the general public as given by ICNIRP [26].

With this new set of action values any adverse indirect effects, e.g. microshocks from touching charged or grounded objects in static or low frequency electric fields and the projectile risk from ferromagnetic objects in static magnetic fields, can be excluded. This provides further guidance to the employer and therefore simplifies the exposure assessment process.

6 Summary

The data given in the figures and tables of section 5, together with other data given in this report, can be used to compile an amended version of the annex of the Directive.

The new and revised exposure limit values guarantee the health and safety of workers without the need for unnecessary and costly measures or unduly impacting the use of certain technologies or industrial processes.

At least one set of directly measureable reference values makes an easy and cost-effective exposure assessment possible, thus avoiding complex, time-consuming and therefore expensive calculations currently necessary to show the compliance of an exposure situation with the exposure limit values.

A new set of action values requires actions and measures only to be taken where they are needed.

As pointed out throughout the report, additional guidance and information can be given to the employer, if necessary, enabling him or her to do most of the exposure assessment by him- or herself, thus saving time and money, while enhancing the safety and health of workers at the same time.

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