DIFFERENT BASIC DOSIMETRIC QUANTITIES FOR THE CHARACTERIZATION OF EXPOSURE TO LOW-FREQUENCY ELECTRIC AND MAGNETIC FIELDS AND THE IMPLICATION FOR PRACTICAL EXPOSURE CONDITIONS AND GUIDELINES

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Abstract—In this paper, the different quantities for characterizing human exposure at extremely low frequencies (ELF) up to 100 kHz are described. It is explained how the incident field is disturbed by the human body and how the in-situ fields and current densities are created in the body. Incident electric and magnetic fields are treated separately. Incident field characteristics such as homogeneity, time dependence, and polarization and body characteristics such as dimensions, shape, and position will influence the induced quantities. The use of in situ fields or of induced current densities to set the basic restrictions is discussed. The methods for deriving the reference levels from the basic restrictions in the international standards such as ICNIRP and IEEE guidelines are mentioned. Elliptical human models have been typically used in the past. In recent years, high-resolution anatomical models have become available. In this case maximum induced field levels or current densities can be determined for each organ. The validity of using elliptical or high-resolution anatomical models to derive reference levels is discussed. Special attention is paid to non-uniform (such as domestic exposure) or partial exposure of the human body.

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INTRODUCTION

ELECTROMAGNETIC FIELDS are governed by the Maxwell's equations. The basic field quantities are: electric field (E) ($V\ m^{-1}$), electric flux density (D) ($As\ m^{-2}$), magnetic field (H) ($A\ m^{-1}$), and magnetic flux density B (T). These are vector quantities. They can be composed out of components in three orthogonal directions. Electric fields are created by electric charges. The electric field is defined by the magnitude and the direction of the force it exerts on a unit charge. Moving charges or currents

create magnetic fields. A sinusoidal time-varying field vector will describe in time an ellipse. This phenomenon is also called elliptical polarization. Special cases are linear and circular polarizations.

In free space or in unperturbed conditions, the low-frequency fields [extremely low-frequency (ELF) fields with frequencies up to 100 kHz considered] are uncoupled: electric fields can be determined from voltage drops and the magnetic fields from currents. In the example of power lines, the electric field will be determined from the voltage on the line and the distance of the line to the ground, and the magnetic fields by the total current flowing on the line (dependent on the loading). Therefore, the electric field will be relatively constant in time while the magnetic field will vary (as the loading of the line is varying as a function of time).

In computational methods advantage is taken of the quasi-static approximation of the Maxwell's equations. Moreover, at ELF frequencies, one can neglect the displacement current in comparison to the conduction term inside the human body. Therefore, it suffices to only consider the conductivity of the tissues. The permittivity values of the tissues do not play a role in the numerical calculations.

In this paper, the mechanism of interaction of ELF fields with the human body is described. The progress in modeling of ELF interaction with the human body is discussed. The complex nature of realistic fields is mentioned and the impact on the guidelines and on compliance verification is shortly discussed.

INDUCED FIELDS, CURRENT DENSITIES, AND CONTACT CURRENTS

When a human body is entering an ELF field, the external fields may be disturbed. The disturbance for the external electric field will be different than for the external magnetic field. As the biological effects relate to the fields and currents inside the body, we focus our attention on the

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induced fields and current densities. These last two quantities are not independent as the induced electric field E and the current density J ($A\ m^{-2}$) in the body are linearly related through Ohm's law.

Induced fields and current densities from an external electric field

In this case, the external electric field will be highly disturbed by the body. The disturbance will depend on the shape, the size, and the position of the body. Charges are induced on the surface of the body. The polarization of the charges induces currents in the body. The currents will be larger in case of a grounded than in case of an isolated one. Again all body parameters will determine the induced currents.

Fig. 1 shows the induced currents in case of a uniform vertical external electric field. As the body is conductive, the external field lines are disturbed such that they arrive nearly orthogonally to the surface of the body. Currents are maximal in regions of the body where a limited area is available for the currents to flow, e.g., in the neck and ankle regions.

Induced fields and current densities from an external magnetic field

The external magnetic field is not or only slightly disturbed because the body is magnetically transparent (non-magnetic: $\mu = \mu_0$ or permeability of free space).

Fig. 1. Induced current density in a human body by a vertical external electric field.

Based on Faraday's law, electric fields and circulating currents will be induced in the body.

The induced current densities are for homogeneous materials proportional to the radius of the loop (cross-section of body determines currents), the frequency, the conductivity and the magnitude of magnetic flux density B . The loops will be orthogonal to the incident magnetic field. So if the magnetic field is oriented front to back, the largest loops and thus the largest current densities will be created as shown in Fig. 2.

Induced contact currents

When a body touches a charged metallic object, contact currents will flow through the body. Even when the human body comes into proximity of an object in a strong field, a current can flow through the air and into the body. This effect is called discharging or sparks.

The magnitude and spatial distribution of electric contact currents depend on the frequency, the size of the charged object, the size of person, and the area of contact.

Realistic fields

The calculation of the fields inside the human body is mostly done through uniform fields. This may be valid under power lines where if there are not many disturbing objects present in the neighborhood of the line the (magnetic and electric) field distribution will be nearly uniform. In-house there is a proliferation of devices that constitute the ELF electromagnetic environment. The fields of these devices are very complex in space and time due to the characteristics of the sources (e.g., burst-like currents in devices that are motor-driven) and the high perturbation of the fields by the human bodies and objects close to the devices. There are only few studies (mostly experimental) concerning domestic ELF fields.

Ainsbury et al. (2005) showed that the domestic magnetic fields are very complex and cannot be characterized by a time-weighted average or peak value. They found that the polarization of the fields must be taken into account. Resultant magnetic fields that are elliptically or circularly polarized have higher rms (root-mean-square) strengths and can thus produce higher current densities in the body in comparison to linearly polarized fields.

Some calculations have been done in non-uniform fields. Gandhi and Kang (2001) investigated the exposure of adults and children to electronic surveillance devices. They found that the limits could be exceeded in the heads of the children as their heads were in considerably higher non-uniform fields from the particular device in comparison to the heads of the taller adults. Other examples are the study of Dawson et al. (1999) on exposure to

Fig. 2. Induced current density in a human body by (a) a vertical and (b) a horizontal external magnetic field.

three-phase current carrying conductors and the study of Nadeem et al. (2004) who investigated magnetic fields from spot welding equipment. No detailed investigation of non-uniform fields from domestic devices has been done. A good step towards a well-established study is the derivation of a non-uniform source model based on the simulations of the fields around the body (Nishizawa et al. 2004) or measurements (Scorretti et al. 2005).

The time-domain behavior of domestic or occupational exposure can also be very complex. Complicated waveforms from sources of pulsed electric and magnetic fields in industry are described by Cooper (2002) and Jokela (2000). In the guidelines, besides the rms value, the peak value and the Fourier components are also used as characteristics of the complex waveforms. The peak value is however a time-domain quantity and the limits are expressed as a function of frequency. In the guidelines $f = 1/(2t_p)$ is for example used as the comparison frequency. t_p is the phase duration of a peak excursion of the quantity under consideration. The phase duration is defined as the time between zero crossings of a waveform having zero mean. The peak value is compared at the comparison frequency to the rms basic restrictions or reference levels multiplied with $\sqrt{2}$. When the Fourier components are used, the sum of the magnitude of the components normalized to the limit values at the frequency of the components should be smaller than 1. This is, however, a very conservative approach.

A better but however a more complex approach is proposed by International Commission on Non-Ionizing Radiation Protection (ICNIRP 2003). It uses the sum of

the products of the amplitude of the Fourier components with a weighting function where the magnitude is equal with the inverse of the peak reference levels. Heinrich showed that this approach still can lead to a significant overestimation (Heinrich 2006). A new, more realistic approach proposed by Heinrich (2006) is based on the physical mechanisms of the stimulation process. The exposure assessment is done in the time domain and determines for basic and complex waveforms the necessary parameters.

Certainly more research is needed on a good metric for complex non-uniform non-sinusoidal ELF exposure and impact of this kind of exposure on the reference levels.

BASIC RESTRICTIONS AND REFERENCE LEVELS

Basic restrictions

The basic restrictions are defined in terms of induced current densities. However, a consensus is growing that the induced electric field is the basic quantity for the effects of neural stimulation based on voltage-gated ion channels. This recommendation was made in the electromagnetic field (EMF) exposure workshop held in Brussels in 2000 (Sheppard et al. 2002) and has been incorporated in the Institute of Electrical and Electronics Engineers, Inc., guidelines (IEEE 2002). The same opinion was expressed by an ad-hoc expert group advising the National Radiological Protection Board (NRPB) (McKinlay et al. 2004) and at the ICNIRP/World Health Organization (WHO) workshop held at the NRPB (Blakemore et al. 2003).

It has been suggested that the induced field should be averaged over 1 mm³ volume of nerve tissue. However, the discretization grid of the available human models is mostly larger than 1 mm due to limited computer memory. So, looking for the maximally averaged value comes down to finding the calculated maximum of the induced electric field. The maximum single-voxel value is, however, very sensitive to staircasing effects and boundary conditions especially when there is a large difference between the conductivity of neighboring voxels. Therefore, Dimbylow (2005) suggests using the 99th percentile value i.e., the value that is exceeded in only 1% of the voxels of a particular organ. This 99th percentile value has been used by Dawson et al. (2001) to make an uncertainty evaluation of the numerical calculations of induced fields and current densities. The use of this 99th percentile value would certainly have its impact on the basic restrictions as well as on the reference limits.

Reference levels

Reference levels are defined for the external unperturbed fields (ICNIRP 1998; IEEE 2002). If the measured fields are below the defined levels, the basic restrictions will be fulfilled. The reference levels are derived from the basic restrictions by determining the external fields that realize the levels of the basic restrictions in the body. For the purpose of demonstrating compliance with the basic restrictions, ICNIRP states that the reference levels for the electric field and magnetic flux density strengths should be considered separately and not additively. Reference levels expressed in terms of the rate of the magnetic flux density change dB/dt can also be derived from the basic restrictions.

When the ICNIRP or IEEE guidelines were created, simple models were used. In the case of incident magnetic fields, simple circular conductive loops are used to estimate the induced current density in each organ using Faraday's law. A better approach is to use ellipsoidal model for a human and incident field oriented such that a maximum coupling with the body is achieved. The IEEE reference limits are derived using an ellipsoidal model for the head and the torso of a large individual with uniform conductivity and a constant magnitude and relative phase of the field over the body (IEEE 2002). The advantage of these simple models is that an analytical solution is available delivering known uncertainties on the obtained values. On the other hand, as these models are homogeneous in conductivity they do not allow calculating the induced current densities for individual organs.

In the case of incident electric fields, the size, shape, and position will have a large effect on the induced surface charge density and consequently on the currents

inside the body. In addition, the current density distribution will vary inversely proportional to the cross-sections of the body resulting in high values in the neck and ankles. Therefore, the use of elliptical models is not appropriate in this case.

As the models are very simple, the result is not very representative for realistic exposure. As now high-resolution anatomical models are available, more realistic reference levels could be derived (Dimbylow 1996, 2005; Stuchly and Dawson 2000; Nagaoka et al. 2004). A comparison of the voxel models and the review of numerical dosimetry for ELF can be found in McKinlay et al. (2004). Adult male and female models with a resolution of 2 mm voxel size are available. In most cases more than 30 tissue types are identified. They are derived from MRI (magnetic resonance imaging) images. The anatomical models allow determining the induced fields within a single organ or part of an organ. However, the accuracy of the calculated fields will depend on the variation in dielectric parameters of tissues, and the representativeness of the phantom model (variations in anatomy and posture, models for children and adults). Child models that have been used in the calculations are derived from adults by uniform scaling. However, this is not a correct approach, as the dimensions of the organs do not scale in the same way as the overall dimensions of the body. Different scaling for the head and the rest of the body has been implemented by Hirata et al. (2001). Although difficult to obtain, correct child models derived from, e.g., whole-body MRI scans are needed.

In order to give full credibility to the numerical calculations, experimental validation should be done. Little or no experimental validation has been done up to now.

Compliance verification

In most cases compliance is verified through the comparison of the measured unperturbed incident electric and magnetic fields and the reference levels. However, as already indicated, the reference levels have been derived through simulations with very simple models of humans. Therefore, uncertainty factors were taken into account while deriving the reference levels, which could lead to a too conservative approach.

Therefore, the NRPB, now part of the Health Protection Agency (HPA) of the UK, suggested a three-step procedure for compliance verification (NRPB 2005). In the first step, the free-space fields are determined and the exposure levels are compared with the reference limits (e.g., ICNIRP guidelines). In the case of non-compliance with the first step, step 2 is recommended. The maximum permitted incident electric and magnetic field levels are determined from the basic restrictions through calculations (worst-case conditions) with anatomically correct

models. These values are calculated for idealized exposure geometries, uniform fields, grounding conditions, and direction of the field that results in maximum coupling with the body. This step delivers less conservative values for the incident electric and magnetic flux density fields in comparison with the reference levels. Finally, if the measured electric or magnetic flux density values are not compliant with the maximally permitted incident electric and magnetic flux density field levels calculated in step 2, step 3 must be executed. In step 3 the basic restrictions are verified in phantoms for actual exposure conditions. Such conditions might include partial body exposure, non-uniform fields, actual field characteristics, and correct distance to the source.

Although this approach could help in situations where it is very difficult to comply with the reference levels, step 2 should still ensure that the basic restrictions are fulfilled.

Furthermore, the fields in a home environment are very complex. One measurement in space and time will not be sufficient to verify the compliance with the limits. Procedures are lacking for more accurate compliance verification measurements.

CONCLUSION

This paper deals with the basic quantities for characterizing exposure from ELF fields. There is a growing consensus that the induced electric field should be used instead of induced current density as basic quantity representing the cause of potential biological effects.

In the guidelines, reference levels have been derived from the basic restrictions using simple models. Nowadays, correct inhomogeneous anatomical models are available on the basis of which more realistic reference values could be calculated. However there is still a lack of experimental validation to warranty that the values calculated are representative for real induced fields and current densities.

Unlike fields under power lines, the fields in the homes and in the industry are very non-uniform and very complex as a function of time. Because of the close distance, people may also be partially exposed. Good metrics for these complex field patterns and correct methods for compliance verification are still under development.

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