Radiation Protection Dosimetry (2009), Vol. 137, No. 3–4, pp. 247–251
Advance Access publication 19 October 2009
doi:10.1093/rpd/ncp226

REVIEW OF OPEN PROBLEMS IN ASSESSING COMPLIANCE WITH 2004/40/EC DIRECTIVE EXPOSURE LIMIT VALUES FOR LOW-FREQUENCY CURRENT DENSITY BY MEANS OF NUMERICAL TECHNIQUES

Nicola Zoppetti[1,]* and Daniele Andreuccetti[1]
[1]Istituto di Fisica Applicata 'Nello Carrara' (IFAC), Consiglio Nazionale delle Ricerche (CNR), via Madonna del Piano 10, I-50019 Sesto Fiorentino (FI), Italy

The endorsement process of the 2004/40/EC Directive (still in progress) has led to a critical analysis of the ICNIRP Guidelines, on which the directive is based. In particular, some known problems affect the applicability of the numerical techniques needed for checking compliance with limits at low frequency. A review of these open problems is presented in the paper, highlighting how such problems deal more with pre-processing and post-processing steps than with the core numerical calculation of the current density.

INTRODUCTION

Directive 2004/40/EC[(1)] is the reference regulation dealing with occupational exposures to electromagnetic fields in Europe. This directive is based on ICNIRP Guidelines[(2)] that introduce reference levels for external fields (action values in the directive) and basic restrictions for internal induced quantities (exposure limit values in the directive). Violation of the action values does not necessarily imply violations of exposure limit values. In fact, according to the directive, 'if the action values are exceeded, the employer shall assess and, if necessary, calculate whether the exposure limit values are exceeded'.

At low frequency, the reference internal quantity is the current density, which can be calculated using different types of methods. A possible choice is the ones based on the so-called quasi-static approximation, according to which the exposures to magnetic and electric fields can be treated separately. This paper reviews the main steps and difficulties that have to be faced in order to verify the compliance of exposure limit values for the current density. As far as the calculation of the current density is concerned, the paper will refer to quasi-static numerical methods. The discussion is more general on the other subjects, such as body models and post-processing.

MAIN ELEMENTS IN A NUMERICAL ANALYSIS OF LOW-FREQUENCY CURRENT DENSITY

The calculation of the current density induced by low-frequency electric and magnetic fields is a multi-step process that is made up of several components, as represented in Figure 1.

Here as follows, the main critical issues and open problems dealing with each of the blocks represented in Figure 1 will be discussed.

DIGITAL BODY MODELS

Recently, several numerical models of the human body have been developed in research environments[(3–5)].

To be used at low frequencies, each segment of the body model has to be classified into a set of recognised tissue. This is because the preferred imaging technique is magnetic resonance (MR) and the data available after MR scans cannot be directly linked to the electrical properties of tissues at low frequencies. A two-step approach is usually applied: first, the proper tissue is 'attached' to each segment; then, a parametric model is applied in order to calculate the tissue characteristics at the desired frequency.

The state of the art in parametric models of biological tissues' electrical properties was developed by Gabriel *et al.*[(6)] This model is greatly used also at low frequencies, even if the authors admit that '*... it is possible that the dielectric parameters below 1 kHz may be undercorrected. This source of errors may affect the dielectric parameters by up to a factor of two*'. Moreover, at low frequencies, the individual variability of electrical parameters of biological tissues is greater than at higher frequencies.

Another problem regards the posture of the exposed subject, since digital voxel models usually represent a standing subject with the arms along the body, in contact with it. In recent times, some application programs were developed, in both academic and commercial environments for putting voxel

*Corresponding author: N.Zoppetti@ifac.cnr.it

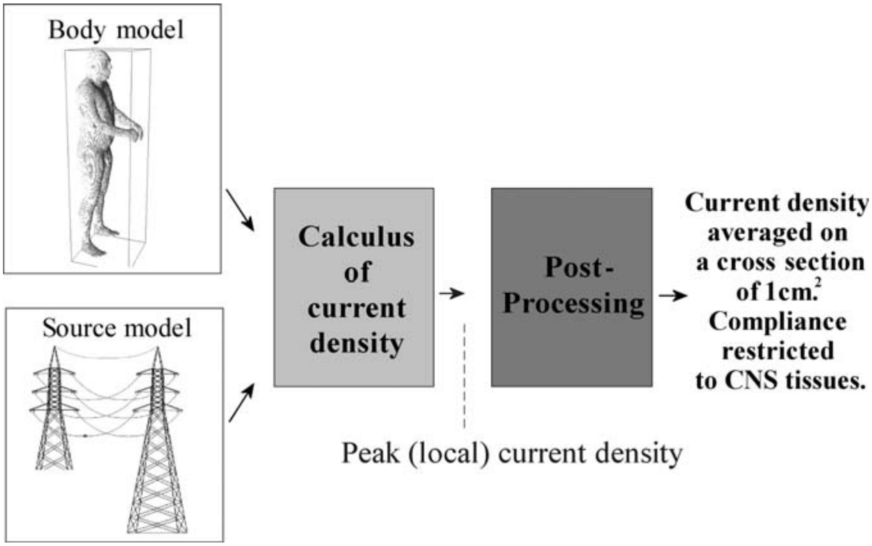

Figure 1. Main elements in a numerical study of the current density induced in the human body at low frequency.

models in realistic postures[7]. In Figure 2, an example of a postured body model is represented that was used in a study regarding current density induced in the body of a worker in the vicinity of a small induction oven[8].

SOURCE MODELS AND NUMERICAL METHODS FOR THE EVALUATION OF CURRENT DENSITY

At low frequency, the so-called 'quasi-static' conditions hold. The applicability of these conditions to numerical dosimetry is discussed in detail in ref. (9). In quasi-static conditions, since electric and magnetic fields can be treated separately, the dosimetric problem can be separated in two independent problems, referred to as 'magnetic' and 'electric problem' here as follows. As represented in Figure 3, the source modelling can be treated independently from what happens inside the exposed subject, and this results in a further separation between the so-called 'external' and 'internal' problems.

Due to quasi-static approximation, the magnetic field inside the exposed subject can be considered to be unperturbed by the presence of the exposed subject. Consequently, the solution of the magnetic external problem consists of the distribution of the impressed field in the volume occupied by the body model. The distribution of the impressed magnetic field is then used as the source term in the solution of the magnetic internal problem.

In the case of exposure to the electric field, the human body cannot be considered to be transparent during the solution of the external problem. This

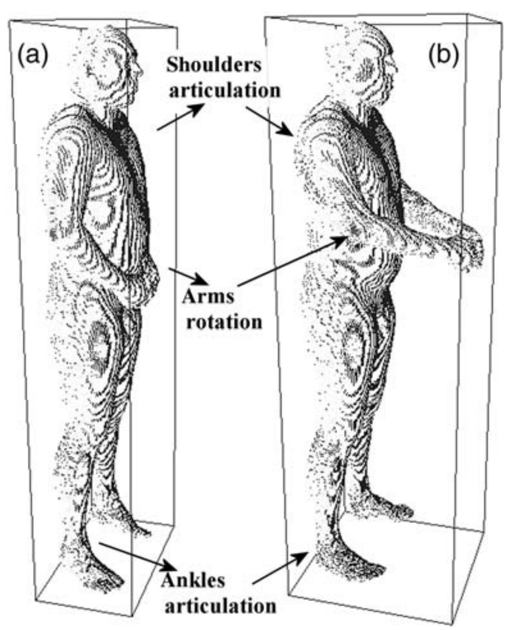

Figure 2. Articulation of a voxel phantom.

implies that the electric external problem usually regards big volumes that encompass both field sources and exposed subjects. This can lead to the explosion of memory requirements, which can be overcome with techniques such as non-uniform gridding or the use of different representation of the scenario at a higher and higher resolution[10]. The

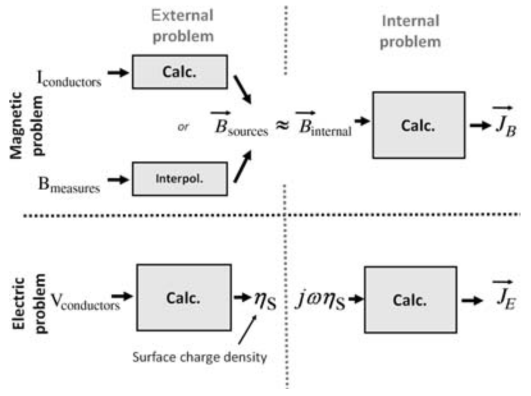

Figure 3. Sub-problems in calculation of low-frequency current density by means of quasi-static methods.

electric internal problem can be solved by using the same methods utilised for the internal magnetic one, but by considering as the source term the time variation of the surface charge density induced by the external electric field. In this case the rate of convergence to the solution is usually slower than in the magnetic case and the use of preconditioning techniques is suitable for reducing the computation time.

The main numerical methods that use quasi-static approximation are cited in ref. (9).

In general, the calculation of the current density induced by a low-frequency electric or magnetic field is diffusely treated in the literature and, even if this may be onerous, it is affected by known accuracy[11] and can be considered as a 'straightforward' process.

POST-PROCESSING

Some of the main open problems in the normative application are caused by certain additional prescriptions that give rise to the quandaries presented here as follows.

Surface averaging over a cross section of 1 cm^2

To verify compliance with exposure limit values, current densities must be averaged over a cross section of 1 cm^2, as is prescribed by Note 3 of Table 1 of the 2004/40 Directive. ('Because of the electrical inhomogeneity of the body, current densities should be calculated as averages over a cross section of 1 cm^2 perpendicular to the current direction'.)

Dawson *et al.*[12] introduced a simplified algorithm for the current density surface averaging that is widely used in the literature. According to it, 'the components of the current density average associated with a given voxel are computed by averaging the perpendicular components of current density over squares with 1-cm edges centred on the voxel and parallel to the three principal Cartesian planes. The resulting vector field is treated similarly to the current density itself in dosimetry computations'. This algorithm introduces two main approximations. First, it uses square cross sections that intersect different portions of surrounding voxels, depending on their orientation. Secondly, and more important, the cross sections used to average the current density are not necessarily perpendicular to the current direction, as required by the Directive.

In ref. (13), an algorithm that rigorously implements the directive's requirements is applied to a realistic case of exposure in a working environment. The results obtained with this algorithm differ significantly from the ones obtained by applying the simplified algorithm to the same case. This comparison shows how the choice of the surface algorithm can be considered to be an important source of (methodological) uncertainty.

On the other hand, even if the simplified algorithm does not implement the directive requirements, it should be noted that it is directly applicable also to a current density distribution with circular or elliptical polarisation. This is due to the fact that averaging cross sections are parallel to the three main coordinate planes, and are not linked to the actual current density orientation.

Limitation to the central nervous system

Surface averaging is not only a source of ambiguity by itself, as presented in the previous paragraph, but gives rise to problems in conjunction with another prescription of the Directive. In fact, Note 2 of Table 1 specifies that the 'exposure limit values on the current density are intended to protect against acute exposure effects on central nervous system (CNS) tissues in the head and trunk of the body'.

When the application point of the averaging cross section is close to a surface separating an organ of the CNS from different tissues, the averaging cross section will possibly intersect voxels that do not belong to the CNS. For instance, the spinal chord (or the structure composed by the spinal chord and the cerebro-spinal fluid) has, in many cases, a cross section smaller than 1 cm^2[14]. In these situations, it should be decided if the contributions to the average coming from tissues not belonging to the CNS need to be considered.

Different approaches to CNS limitation have been presented and discussed in the literature, in both past[12] and more recent works[14,15]. For example, by using the so-called 'full averaging' approach[12], the averaging application point is always taken in a voxel that belongs to the CNS. However, the contributions of all other voxels (even ones not belonging to the CNS) that intersect the averaging surface are also fully considered. On the contrary, by using a 'tissue-specific' approach[12], the contributions of the tissues not belonging to CNS are zero-weighted in the surface average expression. Independently of the preferred choice, this can be considered to be another source of methodological uncertainty[13].

Composition of current density induced by the electric and magnetic fields

ICNIRP Guidelines prescribe considering the effects of electric and magnetic fields separately. There are cases in which the phase delay between voltage and current in source conductors is known. This is the case, for example, of very high-voltage power lines.

If the correct phase is assigned to voltage and current in conductors during the solution of the dosimetric problem, in the end, the currents induced by the electric and magnetic fields can be summed according to the following expressions, where, using the symbolic notation, p indicates *in-phase* part and q the *in-quadrature* part of the current density:

$$\begin{aligned} \vec{J}_B &= \vec{J}_{pB} + j\,\vec{J}_{qB} \\ \vec{J}_E &= \vec{J}_{pE} + j\,\vec{J}_{qE} \\ \vec{J}_{B+E} &= \left(\vec{J}_{pB} + \vec{J}_{pE}\right) + j\,\left(\vec{J}_{qB} + \vec{J}_{qE}\right) \end{aligned} \quad (1)$$

In these cases, considering the total current is not only technically possible but is also a correct representation of the physic of the problem.

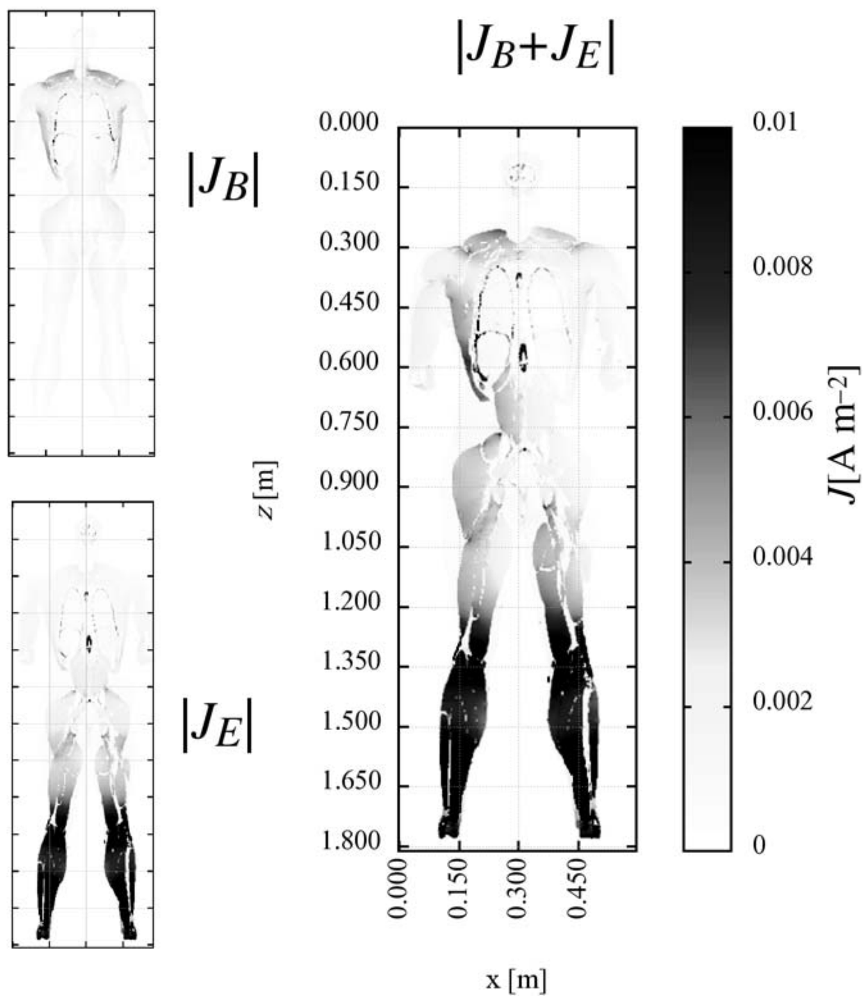

Figure 4. Composition of 'magnetically' and 'electrically' induced current densities on a sagittal section of the exposed subject.

In Figure 4, the distribution of the current densities defined by equation (1) is represented in the case of a man standing under one of the conductors of a three-phase, very high-voltage power line In this case, voltage and current on each conductor are considered to be in phase (resistive load), and the exposed subject is grounded.

As can be noted, the total current shows a typical anti-symmetric distribution.

CONCLUSIONS

The calculation of the current density induced by low-frequency electric and magnetic fields has been thoroughly studied in the literature. By using the best practice methods, the uncertainty that affects calculation methods of the current density can be reduced to a reasonable level, and naturally tends to decrease with the improvement in calculation techniques and with the deepening of the theoretical aspects.

Nevertheless, the application of the normative prescriptions also entails some post-processing tasks that are somewhat ambiguous, and quandaries exist as to how they should be applied. Moreover, the surface averaging of the current density becomes completely inapplicable in the general case of elliptical field polarisation, since the orientation of the averaging cross section is not defined.

FUNDING

Part of the research described in this paper, and in particular the one regarding current density surface average, was carried out in the framework of the contract no 18455 between IFAC-CNR and Trenitalia Spa, signed on 20 December 2007.

REFERENCES

1. *EU 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)*. Official J. European Union Legislation 184 **47**, 1–9 (2004).
2. *ICNIRP Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 300 GHz)*. Health Phys. **74**, 494–522 (1998).
3. Dimbylow, P. J. *The development of realistic voxel phantoms for electromagnetic field dosimetry.* Proceedings of the International Workshop on Voxel Phantom Development (NRPB Report), 1–7 (1996).
4. Dimbylow, P. J. *Development of the female voxel phantom, NAOMI, and its application to calculations of induced current densities and electric fields from applied low frequency magnetic and electric fields.* Phys. Med. Biol. **50**, 1047–1070 (2005).
5. Nagaoka, T., Watanabe, S., Sakurai, K., Kunieda, E. and Watanabe, T. *Development of realistic high-resolution whole-body voxel models of Japanese adult male and female of average height and weight and application of models to radio-frequency electromagnetic-field dosimetry.* Phys. Med. Biol. **49**, 1–15 (2004).
6. Gabriel, S., Lau, R. W. and Gabriel, C. *The dielectric properties of biological tissues: III. Parametric models for the dielectric spectrum of tissues.* Phys. Med. Biol. **41**, 2271–2293 (1996).
7. Watanabe, S., Nagaoka, T., Sakurai, K., Watanabe, T., Kunieda, E., Taki, M. and Yamanaka, Y. *Development of voxel male and female whole-body models and dosimetry.* URSI Genral Assembly, Maastricht, The Netherlands, KB.05, 130 (2002).
8. Zoppetti, N. and Andreuccetti, D. *The influence of the surface averaging procedure of the current density in assessing compliance with ICNIRP low frequency basic restrictions by means of numerical techniques.* Phys. Med. Biol. **54**, 4835–4848 (2009).
9. Andreuccetti, D. and Zoppetti, N. *Quasi-static electromagnetic dosimetry: from basic principles to examples of applications.* Int. J. Occup. Saf. Erg. **12**(2), 201–215 (2006).
10. Dimbylow, P. J. *Current densities in a 2 mm resolution anatomically realistic model of the body induced by low frequency electric fields.* Phys. Med. Biol. **45**, 1013–1022 (2000).
11. Dawson, T. W., Potter, K. and Stuchly, M. A. *Evaluation of modelling accuracy of power frequency field interactions with the human body.* ACES J. **16**, 162–172 (2001).
12. Dawson, T. W., Caputa, , K. and Stuchly, M. A. *Magnetic field exposures for UK live-line workers.* Phys. Med. Biol. **47**, 995–1012 (2002).
13. Zoppetti, N. and Andreuccetti, D. *Influence of the surface averaging procedure of the current density in assessing compliance with the ICNIRP low-frequency basic restriction by means of numerical techniques.* Phys. Med. Biol. **54**, 4835–4848, (2009).
14. Dimbylow, P. J. *Quandaries in the application of the ICNIRP low frequency basic restriction on current density.* Phys. Med. Biol. **53**, 133–145 (2008).
15. Bahr, A., Bolz, T. and Hennes, C. *Numerical dosimetry ELF: accuracy of the method, variability of models and parameters, and the implication for quantifying guidelines.* Health Phys. **92**(6), 521–530 (2007).