Simplified Dosimetry for Human Exposure to Non-uniform ELF Magnetic Field

Kenichi Yamazaki* Member

Tadashi Kawamoto* Member

Hideo Fujinami* Member

Tsukasa Shigemitsu* Member

Regarding recent concerns on the health effects of ELF (extremely low frequency) magnetic fields, compliance testing in accordance with guidelines in highly non-uniform magnetic field has been a critical issue. In these cases, when the measured maximum magnetic fields on the surface of the human body exceed the reference level, the basic restriction should be investigated in a different way. However, this requires numerical calculation of the induced current or electric field, which is not readily achievable. Therefore, a simplified method for investigation of the conformity with a guideline, particularly one applicable to practical situations, is strongly required. In this paper, a new simplified method that can be used to estimate the maximum induced current from magnetic field measurements in practical complex situations was proposed. This method is based on the reduction rate of the magnetic field within a spherical model. The relationship between the reduction rate of magnetic field and the rate of maximum induced current to that of uniform field exposure was approximated using a simple regression curve. The previously proposed method based on averaging of the magnetic field over a certain area was also investigated. The results obtained in the study have practical values for assessing compliance with guidelines.

Keywords : ELF magnetic field, induced current, guideline, non-uniform magnetic field

1. Introduction

Recent concerns on the health effects of ELF (extremely low frequency) magnetic fields seems to have been an issue of compliance testing in accordance with guidelines based on established threshold of acute biological responses. These guidelines developed recently include those of ICNIRP (International Commission on Non-Ionizing Radiation Protection)⁽¹⁾, HCN (The Health Council of the Netherlands)⁽²⁾, and IEEE/ICES (The Institute of Electrical and Electronics Engineers, Inc./International Committee on Electromagnetic Safety)⁽³⁾.

The method of assessing the relevant quantities related to exposure to magnetic fields under specific circumstances has become a critical issue in discussing the safety of such fields. These internal quantities include induced current density⁽¹⁾⁽²⁾ or induced electric field⁽³⁾ and they are called “basic restrictions” in these guidelines.

Since these internal quantities for humans are not measurable in practice, an alternative measurable quantity, i.e., magnetic field, is provided as a reference (“reference level”⁽¹⁾⁽²⁾ or “maximum permissible exposure”⁽³⁾) to assess compliance with these guidelines. Here, these guidelines assume uniform field exposure as a worst-case scenario to derive the reference level from the basic restriction. Therefore, special consideration should be made for magnetic field exposures which are highly non-uniform over the volume of the human body when the exposures are relatively high compared with the guideline levels.

These exposures can occur in an actual high exposure situations, such as in the direct vicinity of power lines⁽⁴⁾⁽⁶⁾ and electric

appliances⁽⁷⁾⁽⁹⁾. In these cases, when the measured maximum magnetic fields on the surface of the human body exceed the reference level, the basic restriction should be investigated in a different way. However, this requires numerical calculation of the induced current or electric field, which is not readily achievable. Therefore, a simplified method of investigating the conformity with a guideline, particularly one applicable to practical situations (from *in situ* measurement of magnetic field), is strongly required.

Our goal is to provide a simplified method which is of practical value for assessing high exposures relative to guideline levels from magnetic field measurement. Note that the “induced current” is used as a representative of internal quantities in this paper.

2. Background

The quantity of interest to be compared with the basic restriction is the maximum induced current density J_{max} in the human body. The best estimate of J_{max} has been obtained for uniform magnetic field exposure ($J_{max-uniform}$) using high-resolution anatomically correct models⁽⁵⁾⁽⁸⁾⁽¹⁰⁾⁽²⁰⁾. However, because of the complex geometry of magnetic field sources and postures of the human models, and the computer requirements, it is not practical to compute induced currents for a large number of non-uniform exposure scenarios. Therefore, simplified approaches have been proposed for linking actual non-uniform magnetic field exposures to $J_{max}^{(21)(24)}$. These approaches involve the simple conversion of $J_{max-uniform}$ obtainable from articles for uniform exposure using a high-resolution model to J_{max} for the individual geometry using proposed simplified procedures without repeating massive computations. Three types of simplified approaches have been previously proposed by researchers, which are summarized in Table 1. These three approaches differ in how they integrate field

* Central Research Institute of Electric Power Industry
2-6-1, Nagasaka, Yokosuka 240-0196

Table 1. Previously proposed simplified method for estimating J_{max}

Researcher	Field Source	Needed Work	Note
Stuchly et al. (2002) [21]	any	calculaion of B-field average over specific organ of interest	
Kavet, Bracken (2001, 2002) [22, 23]	any	calculaion of B-field average over elliptical cross-section of human body	assumption needs verification
Swanson (2002) [24]	single phase	calculaion of J_{max} using simple analytical formula	

non-uniformity into their estimates and how the approach is implemented in the field. The first method (“field-ratio method”) ⁽²¹⁾ estimates J_{max} at the specific organ of interest using the ratio of the whole body average magnetic field over the organ to the whole-body average magnetic field. The ratio is multiplied with $J_{max-uniform}$ to obtain J_{max} . Here, the average magnetic field is assumed to be the same as the uniform magnetic field. The second method (“simple-source method”) ⁽²²⁾⁽²³⁾ estimates the equivalent (averaged over an elliptical cross section of a human body) magnetic field, and assumes that the maximum induced current density for the non-uniform field is identical to the maximum induced current density for the equivalent uniform field (“ B -field criteria”). The third method estimates $J_{max-uniform}$ analytically in an infinite length of a rectangular cross section located parallel to a single line conductor, which has a simple analytical solution ⁽²⁴⁾.

Our aim is to apply a simplified procedure of estimating J_{max} to the practical complex situations of magnetic field measurements. The previously proposed methods are not satisfactory for our purpose since the first and second methods require the averaging of the B -field (magnetic field) over a volume or a cross section of a human model, and the third method is only applicable for a single line conductor geometry. In addition, the second method (“ B -field criteria”) still needs verification. To fulfill the requirements, we propose a new method in the following section.

3. Proposed Approaches

3.1 Items to be Investigated In this study, two approaches that are applicable to practical situations of magnetic field measurements are proposed. The first one is applicable when the nature of the field source and the distance between the source and the human body are known. The second one uses the reduction rate of the magnetic field on the distant side of a human model, and is applicable even when the nature of the field source and the distance between the source and the human body are unknown.

3.2 Field Sources and Simple Model Typical sources of magnetic fields can be placed in three simple categories with well-known B -field distributions: single-phase infinite line sources (B -field is proportional to the inverse of distance d), multiple-phase line sources (double wires with opposite current direction, spacing D , and B -field is proportional to the inverse of d^2), and magnetic dipole or current loop sources (B -field is proportional to the inverse of d^3). The multi-phase line sources also represent the three-phase line generally used for power transmission. Once exposures are characterized for these simple

Fig. 1. Magnetic field sources and spherical model: (a) single phase line, (b) multiple phase line (double wires with opposite current direction), (c) magnetic dipole

sources, the results can be used to estimate induced currents for actual exposure scenarios.

Here, a simple model for incorporating field non-uniformity is chosen to be a homogeneous sphere with radius R , while in other proposals, an elliptical cross section ⁽²²⁾⁽²³⁾ or rectangular cross section ⁽²⁴⁾ was chosen. The shape has advantages over other shapes, such as (1) all parameters can be scaled by the radius of the sphere, and (2) the model is symmetric in any direction of incident magnetic field.

3.3 Calculation of Induced Current Induced currents inside the sphere model were calculated for the three types of sources by changing d , the distance between the field sources and the surface of the sphere (Fig. 1). The same amplitude of magnetic field B_0 is assumed at the surface of the sphere closest to the field source (position P in Fig. 1) for all the scenarios. The calculation

method adopted was a surface charge method⁽²⁵⁾ modified to enable the use of curved surface charges⁽²⁶⁾. The equation solved is Eq. (1), which was derived from Faraday's law and the continuity equation of the current.

$$-\sigma \nabla \phi \cdot \mathbf{n} = j\omega \sigma A_0 \cdot \mathbf{n} \quad (1)$$

Here, ϕ is the electric scalar potential, ω is the angular frequency, and A_0 is the magnetic vector potential. In the method, the surface charges are unknowns and are solved as a function of ϕ and its gradient. A curved triangular element with nine degrees of freedom is used as the element, and the cubic function of the curve was determined from the three apexes of the triangle and a first order differential coefficient.

An example of the induced current distribution on the X-axis is shown in Fig. 2. A parameter K_J defined by Eq. (2) was newly introduced, and it represents the effects of the field non-uniformity.

$$K_J = J_{\max} / J_{\max\text{-uniform}} \quad (2)$$

$J_{\max\text{-uniform}}$ can be obtained using the well-known simple formula.

$$J_{\max\text{-uniform}} = \pi f R \sigma B_0 \quad (3)$$

Here, f is the frequency, σ is the electrical conductivity of the model, and B_0 is the amplitude of uniform magnetic field. The effect of σ is eliminated in K_J . The results are shown in Fig. 3. In Fig. 3, the horizontal axis is the distance between the source and the surface of the model (d), scaled by the radius of the sphere R . For the multi-phase line, $D/R = 0.05$ was used for the spacing of the double conductors D normalized by R . For the dipole case, the magnetic dipole was represented by a square coil with a side length of L and $L/R = 0.1$. For comparison, estimated values obtained using other methods⁽²²⁾⁻⁽²⁴⁾ are also plotted. It is demonstrated that the shorter the distance d , the lower the maximum induced current density $J_{\max}$ for a given surface magnetic field. The rate of reduction K_J is a function of the distance from the surface of the body to the field source. For larger distances, the field over the body is essentially uniform and the ratio K_J approaches unity. The ratio K_J is multiplied with the $J_{\max\text{-uniform}}$ to obtain the desired $J_{\max}$. This method is applicable when the nature of the field and the distance are known.

3.4 Field Reduction Rate There are cases in which both of the nature of the sources and the distance d are unknown in practical complex situations. Based on the above calculations, another method that is applicable to such situations is proposed. A concept of field reduction rate is introduced. Similar concept has been reported using a spheroid model previously⁽²⁷⁾. We can easily measure the magnetic field at a position on the opposite side of the assumed spherical model (B_{opp}). This is a value generally lower than B_0 , and the reduction rate of magnetic field K_B can be defined by

$$K_B = B_{\text{opp}} / B_0 \quad (4)$$

Fig. 4 shows the plots for K_B and K_J for the three types of magnetic field sources. The figure indicates that the relationships between K_B and K_J for these sources are relatively close and are not dependent on the types of the field sources. An estimation curve that traces maximum value of K_J for each K_B can be drawn as in Fig. 4 and formulated as Eq. (5), which is easy to handle.

$$K_J = K_B^{0.2} \quad (5)$$

Fig. 2. Distribution of induced current on X-axis for each field sources ($d=1\text{ cm}$ and 2 m , $R=10\text{ cm}$, $D=0.5\text{ cm}$)

Fig. 3. Distance characteristics of K_J , the ratio of maximum induced current

Fig. 4. Relation between magnetic field reduction rate and the ratio of maximum induced current

3.5 Comments on “B-field criteria” These calculations can be used to investigate the assumption in the “B-field criteria”⁽²²⁾⁽²³⁾, that is, “the maximum induced current density for the non-uniform field is the same as the maximum induced current density for the equivalent (averaged over an elliptical cross section of a human body) uniform field”. Fig. 5 and Fig. 6 show the difference of K_J estimated using the B-field criteria and that obtained by calculation for a circular cross section of a homogeneous sphere. The horizontal axes are the scaled distance (Fig. 5) and the B-field reduction rate K_B (Fig. 6). The results show that K_J estimated from the B-field criteria (using the averaged magnetic field) underestimates $J_{\max}$, particularly in the case of highly non-uniform field. Fig. 6 can be used to correlate $J_{\max}$ estimated from B-field criteria.

Fig. 5. Difference ratio of maximum magnetic field between true value and estimated value by B-field criteria

4. Discussion

It is not easy to verify the proposed method since there are not enough articles that present induced currents for both uniform and non-uniform exposures. Table 2 summarizes K_J obtained from several articles for single conductor and magnetic dipole fields⁽⁵⁾⁽⁸⁾⁽¹²⁾⁽²⁸⁾. The asterisks indicate estimated values which were not obtained from the corresponding article. Fig. 7(a) and 7(b) show the plots of these results together with a curve obtained by the proposed simplified estimation. Although there is some discrepancy between these values, the estimated values are always conservative ones.

Fig. 6. Difference ratio of maximum magnetic field between true value and estimated value by B-field criteria. Horizontal axis represents the magnetic field reduction rate K_B

Table 2. Rate of maximum induced current K_J calculated for numerical calculation reported in articles

Researcher	Field Source	d (m)	$B_{\max}$ (mT)	$J_{\max}$ (mA/m ²)	K_J	Note (see original article)
Stuchly, Dawson [12] et al.	single phase	0.5	0.08*	0.608	0.315	25kV configuration
		0.5	0.2*	1.73	0.359	138kV configuration
		0.5	0.4*	2.75	0.285	500kV configuration
	uniform		0.01	0.0241		
	[5] single phase	0.3	3.7	28.4	0.099	scenario A
Baraton, Hutzler [28]	single phase	0.3	3.3	25	0.098	scenario B
		0.3	4.0	5.9	0.019	scenario C
	uniform		1	77.3		
	magnetic dipole	0.1	0.02	0.0087	0.394	a) posture
		0.15	0.0133	0.00366	0.025	b) posture
Gandhi [8]	magnetic dipole	0.1	0.0235	0.129	0.497	square loop
		0.072	0.122	0.246	0.100	hair dryer
	uniform	0.042	1.638	3.64	0.111	hair clipper
			1	20.07		

* : estimated values

Fig. 7. Distance characteristics of the ratio of maximum induced current K_J applied to results of numerical calculations reported d in articles: (a) single phase line, (b) magnetic dipole source

5. Conclusion

In this paper, a new simplified method that can be used to estimate the maximum induced current from magnetic field measurements in practical complex situations was proposed. This method is based on the reduction rate of the magnetic field within a spherical model. The relationship between the reduction rate of magnetic field and the rate of maximum induced current to that of uniform field exposure was approximated using a simple regression curve. The previously proposed method based on averaging of the magnetic field over a certain area was also investigated. The results obtained in the study have practical values for assessing compliance with guidelines.

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Kenichi Yamazaki

(Member) was born in Yokohama, Japan, on February 26, 1968. He received his B.S. degree in applied physics from the Science University of Tokyo in 1990 and his M.S. and Ph.D. degrees in Biomedical Engineering from Hokkaido University, Sapporo in 1992 and 2001 respectively. In 1992, he joined the Central Research Institute of Electric Power Industry (CRIEPI). In 2002 and 2003 he has been a visiting scientist at School of Electrical Engineering and Computer Science, Washington State University, Pullman, WA, USA. His research interests include biological effects of electromagnetic fields and power line electromagnetics. Dr. Yamazaki is a member of IEEE and Bioelectromagnetics Society.

Tadashi Kawamoto

(Member) was born in Osaka, on November 26, 1953. He received his B.S. degree in physics from the Tokyo University of Science, in 1979 and Ph.D. degree in electrical engineering from Kyoto University in 2002. He joined CRIEPI in 1974 and has been engaged in the study of numerical calculations of electric and magnetic fields and eddy currents related to design of high voltage apparatuses and electromagnetic environment. Dr. Kawamoto is a member of IEEE.

Hideo Fujinami

(Member) was born in Tokyo, on December 2, 1952. He received his B.S. and M.S degrees in electrical engineering from Seikei University, Tokyo in 1976 and 1978, respectively. He received his doctorate degree in electrical engineering from Tokyo University in 1994. In 1978 he joined CRIEPI, and has been engaged in basic research on SF₆ gas insulation, the study of lightning, and power line electromagnetics. In 1989 and 1990, he stayed as a guest researcher at the electrical engineering department of The University of Manitoba, Canada. Dr. Fujinami is a senior member of IEEE.

Tsukasa Shigemitsu

(Member) was born in Oita, Japan, on February 27, 1948. He received the B.S., M.S. and Ph.D. degrees in electronic engineering from Hokkaido University, Sapporo in 1971, 1973, and 1979, respectively. From 1974 to 1976, he was an assistant researcher at Max Planck Institute for Physiology, Dortmund, Germany. In 1980, he joined CRIEPI, and has been engaged in the study of biological effect of electromagnetic fields. Dr. Shigemitsu is a member of IEEE, and Board member of Bioelectromagnetic Society from 2003 to 2006.