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LOW-FREQUENCY TRANSIENT ELECTRIC AND MAGNETIC FIELDS COUPLING TO CHILD BODY

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Much of the research related to residential electric and magnetic field exposure focuses on cancer risk for children. But until now only little knowledge about coupling of external transient electric and magnetic fields with the child's body at low frequency transients existed. In this study, current densities, in the frequency range from 50 Hz up to 100 kHz, induced by external electric and magnetic fields to child and adult human body, were investigated, as in residential areas, electric and magnetic fields become denser in this frequency band. For the calculations of induced fields and current density, the ellipsoidal body models are used. Current density induced by the external magnetic field (1 μT) and external electric field (1 V/m) is estimated. The results of this study show that the transient electric and magnetic fields would induce higher current density in the child body than power frequency fields with similar field strength.

INTRODUCTION

Some epidemiological studies in the past stated the existence of positive associations between cancer and leukaemia, occurring in children and the configuration of nearby residential electric power lines, often referred to as 'the wire code'[1,2]. Several reports on this subject have appeared since Wertheimer and Leeper[1] who first pointed out the possibility of an association between childhood mortality due to cancer and proximity of homes to power distribution lines with what is called 'high current configuration'. So far, there have been more than a dozen studies on childhood cancer and its possible causes by exposure to power frequency magnetic fields produced by nearby power lines[1,3–7]. The fact that the results for leukaemia that were based on proximity of homes to power lines had been relatively consistent led the U.S. National Academy of Sciences (NAS) Committee to conclude that children living near power lines appear to be at increased risk of leukaemia[8].

Over the years, there has also been substantial interest in whether there is an association between magnetic field exposure and childhood brain cancer, the second most frequent type of cancer found in children. However, the recent studies completed after the NAS Committee's review fail to provide support for an association between brain cancer and children's exposure to magnetic fields and also, whether the source was power lines or electric blankets. It is also not clear from the report whether magnetic fields were estimated by calculations or by wire codes[5,9,10].

The most intensively investigated environmental factor has been the time-weighted average magnetic fields associated with electric currents on power lines and grounding systems. A large U.S. Case Control Studies to test whether childhood acute lymphoblastic leukaemia is associated with exposure to 60-Hz magnetic field was published by Ref. (4). According to some workers in this field[11–13], the power lines were the most important source of exposure when the magnetic field due to line was greater than ~0.2 μT. The result of the study indicated that children who lived close to a power line had a higher magnetic field exposure than other children. Most of the research in this area has been associated with power frequencies and there are relatively few publications in the frequencies associated with transient fields and these are mostly studies of characteristic compositions of these fields.

In recent years, research has been conducted to characterise transient electric and magnetic fields in residential areas[14–16]. Transient fields in residential environments depend on the electric power lines, grounding systems, switch-gear and wire codes. According to Ref. (15), homes in urban areas had more transients than homes rural areas.

Transients occur with a large number of different waveforms that it did not seem feasible for us to identify a small number of standard waveforms on which to base our analysis. According to Ref. (17), any transient signal, $f(t)$, can be written as:

$$f(t) = \int_{-\infty}^{\infty} \mathrm{d}(\omega) f(\omega) \mathrm{e}^{j\omega t} \quad (1)$$

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where ω is angular frequency, $j = \sqrt{-1}$, and $f(\omega)$ defines the frequency spectrum of $f(t)$. If this signal is passed through a linear system (e.g. electric or magnetic field coupling to a conducting body) whose transfer function for a sinusoidal input is $T(\omega)$, then the transient output signal $Q(t)$ can be defined as:

$$Q(t) = \int_{-\infty}^{\infty} \mathrm{d}(\omega) T(\omega) f(\omega) \mathrm{e}^{j\omega t} \quad (2)$$

Hence, the response of the system to a transient input signal, $f(t)$, can be obtained by understanding its response to a sinusoidal input with frequency spanning 'frequency content' of the transient signal.

The present study analyses whole-body exposure of homogeneous ellipsoids shaped child models to uniform sinusoidal electric and magnetic fields with frequency up to 100 kHz. This frequency range was chosen as it is the practical upper limit for dosimetric concern because of the time constants (>10 μs) inherent to biological signalling within cell membranes[2].

The International Commission on Nonionizing Radiation Protection (ICNIRP) general public reference level for induced current J_{rms} is specified as 2 mA m^{-2} in the frequency range 4 Hz to 1 kHz, and f/500 mA m^{-2} in the frequency range 1–100 kHz (where f is the frequency in hertz)[18].

For the past 25 y, researchers have investigated a possible link between exposure to power frequency (50/60 Hz) of residential magnetic fields and childhood leukaemia cases. Thus, the International Agency for Research on Cancer (IARC) classified extremely low frequency magnetic fields as a 2B carcinogen. These classifications are for between average residential magnetic fields >0.3–0.4 μT and childhood leukaemia[12,19]. Presentation of a dosimetric approach about induced current density of transient electric and magnetic fields in the band of 50 Hz to 100 kHz was aimed

COUPLING MECHANISMS BETWEEN FIELDS AND THE BODY

The interaction of time-varying electric fields with the human body results in the flow of electric charge (i.e. electric current, the polarisation of bound charge, formation of electric dipoles), and the reorientation of electric dipoles already present in tissue. The relative magnitudes of these different effects depend on the electrical properties of the body (i.e. its electrical conductivity and permittivity). Electrical conductivity and permittivity vary with the type of body tissue and also depend on the frequency of the applied field. External electric fields induce a surface charge on the body. The results obtained for induced currents in the body and for the distribution of these currents depend on the exposure conditions, size and shape of the body, and on the body's position in the field.

The physical interaction of time-varying magnetic fields with the human body results in induced electric fields and circulating electric currents. The magnitudes of the induced fields and the current densities are proportional to the radius of the loop, the electrical conductivity of the tissue and the rate of change and magnitude of the magnetic flux density. For a given magnitude and frequency of a magnetic field, the strongest electric fields are induced where the loop dimensions are the greatest. The exact path and magnitude of the resulting current induced in any part of the body will depend on the electrical conductivity of the tissue.

METHODS AND MODELS OF ANALYSIS

The surface of an ellipsoid is defined by the equation:

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} + \frac{z^2}{c^2} = 1 \quad (3)$$

where x, y and z are rectangular coordinates, and the size and shape of the ellipsoid are determined by the three parameters a, b and c where $c \leq b \leq a$.

A basic ellipsoid child model is shown in Figure 1. When using an ellipsoid to model a person, $2a$ defines the person's height, $2b$ defines the person's width (measured from hip to hip) and $2c$ defines the person's 'depth' (measured approximately from the surface of the abdomen to buttocks). Table 1 gives the values of a, b and c in the ellipsoid models of children of various ages and average man[20]. Conductivity and dielectric constant of the selected homogeneous body model for various frequencies can be seen in Table 2[20].

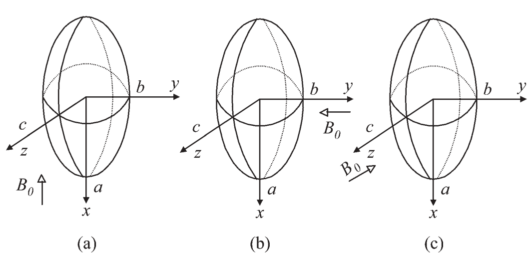

Figure 1. Ellipsoid models representation: (**a**) magnetic field is aligned with the major axis of the body ($B_0//a$), (**b**) magnetic field is aligned with the intermediate axis of the body ($B_0//b$) and (**c**) magnetic field is aligned with the minor axis of the body ($B_0//c$).

Table 1. Ellipsoid parameters for selected body models.

Selected models	a(m)	b(m)	c(m)
Ten-year-old child	0.69	0.143	0.078
Five-year-old child	0.56	0.12	0.069
One-year-old child	0.37	0.095	0.068
Average man	0.9	0.2	0.1

Table 2. Electrical properties of homogeneous body models.

Frequency	Dielectric constant ε_r	Conductivity σ (S m^{-1})
50 Hz	1×10^6	0.1
100 Hz	7 × 105	0.15
1 kHz	1 × 105	0.15
10 kHz	3 × 104	0.2
100 kHz	1 × 104	0.3

Current density and electric field induced by external electric field

The uniform electric field, E, induced inside an ellipsoid by external uniform vertical electric field, E_0, is given by equation (4):

$$E = \frac{j\omega\varepsilon_0}{\sigma^*}\frac{E_0}{A} \tag{4}$$

where $\sigma^* = \sigma + jw\varepsilon_r\ \varepsilon_0$ is the complex conductivity and

$$A = \frac{abc}{2}\int_0^\infty \frac{d\xi}{(\xi + a^2)\sqrt{(\xi + a^2)(\xi + b^2)(\xi + c^2)}} = abc\left(\frac{[F(\phi, k) - E(\phi, k)]}{((a^2 - b^2)(a^2 - c^2)^{1/2})}\right)$$

with

$$F(\phi, k) = \int_0^\phi (1 - k^2 \sin^2\theta)^{-1/2} d\theta$$

$$E(\phi, k) = \int_0^\phi (1 - k^2 \sin^2\theta)^{1/2} d\theta$$

and

$$k = \sqrt{\left(\frac{a^2 - b^2}{a^2 - c^2}\right)}, \phi = \sin^{-1}(\frac{a^2 - c^2}{a^2})^{1/2}$$

where $F(\phi, k)$ and $E(\phi\ k)$ are the incomplete elliptic integrals of the first and second kinds, respectively, and k is the modulus of these elliptic integrals. When the external electric field is vertical to the body, the induced electric field becomes maximum. For other orientations of external electric fields, mathematical details can be seen in the open literature[21].

The current density induced by electric field can be expressed as:

$$\vec{J} = \sigma\vec{E} \tag{5}$$

where σ is the electrical conductivity of the human model. Interactions of 50/60 Hz magnetic fields with a biological body can be considered, for the wavelength of the magnetic field is much larger in comparison to the size of the biological body. It can be shown from Faraday's and Ampere's laws that the secondary magnetic field produced in a biological object by the current flow induced by the external magnetic field can be neglected. So the magnetic field inside the biological body is considered uniform[22].

Mathematical relations for coupling of uniform magnetic field to ellipsoid

Consider a magnetic field, Bo, aligned parallel to the x axis. It can be shown that the induced electric field is in the y–z plane and is everywhere tangent to the ellipse $(y/b)^2 + (z/c)^2 = \eta^2$, where $1 \geq \eta \geq 0$[23,24]. The strength of the induced field E is[23]:

$$E = \frac{\omega B_0}{b^2 + c^2}\sqrt{b^4 z^2 + c^4 y^2} \tag{6}$$

The values of $J_{\max}$ and J_{rms} induced inside the ellipsoid are:

1. B_0 is aligned with a on x axis:

$$J_{\max} = \sigma B_0 \omega \frac{b^2 c}{b^2 + c^2}, J_{\text{rms}} = \sigma\frac{\omega B_0}{\sqrt{5}}\frac{bc}{\sqrt{b^2 + c^2}} \tag{7}$$

2. B_0 is aligned with b on y axis:

$$J_{\max} = \sigma B_0 \omega \frac{a^2 c}{a^2 + c^2}, J_{\text{rms}} = \sigma\frac{\omega B_0}{\sqrt{5}}\frac{ac}{\sqrt{a^2 + c^2}} \tag{8}$$

3. B_0 is aligned with c on z axis:

$$J_{\max} = \sigma B_0 \omega \frac{a^2 b}{a^2 + b^2},$$

$$J_{\text{rms}} = \sigma\frac{\omega B_0}{\sqrt{5}}\frac{ab}{\sqrt{a^2 + b^2}} \tag{9}$$

INDUCED CURRENT DENSITIES

Table 3 depicts the calculated induced current densities when the ellipsoidal models are exposed to 1 V/m external electric field. Table 4 depicts the calculated induced current densities when the ellipsoidal models are exposed to 1 μT external magnetic field.

Figure 2 depicts results of the maximum induced current density in different body models versus different external magnetic field orientations for frequency of 50 Hz. Induced current density in all body models is the maximum for B_0 aligned with c on z axis. Table 5 shows calculated maximum induced current densities inside the ellipsoidal models exposed to 1 μT magnetic field for orientation of $B_0//b$. Table 6 depicts maximum induced current densities for the external magnetic field vertical to the body ($B_0//a$).

Table 7 presents the calculated induced current densities when the ellipsoidal models are exposed to 1 μT magnetic field for orientation of $B_0//c$

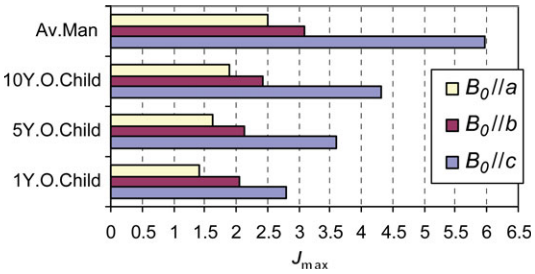

Figure 2. Results of the maximum current density values J_{max} [μA/m^2 /(μT)] in different body models for frequency of 50 Hz.

CONCLUSIONS

In this paper, for ellipsoidal body models, with 1 μT magnetic and 1 V/m electric field exposure, induced current densities have been analysed. Results vary with the orientation of field or the size of body. When the external magnetic field is applied in parallel to the long axis of body ($B_0//a$, i.e. aligned with the long

Table 3. Induced current density in body models by external electric field density value of 1 V/m which is vertical to the body.

Body models	J [μA/m^2/(V/m)]				
	50 Hz	100 Hz	1 kHz	10 kHz	100 kHz
Average man	0.0722	0.1443	1.443	14.392	142.0
Ten-year-old child	0.0744	0.1488	1.4878	14.836	146.38
Five-year-old child	0.068	0.1361	1.3604	13.567	133.86
One-year-old child	0.0448	0.0897	0.8967	8.942	88.2269

Table 4. Induced current density in body models by 1 μT external magnetic field which is perpendicular to front of the body.

Body models	J_{max} [μA/m^2/(μT)]				
	50 Hz	100 Hz	1 kHz	10 kHz	100 kHz
Average man	5.987	17.9625	179.6252	2395	35 925
Ten-year-old child	4.3075	12.9224	129.229	1723	25 845
Five-year-old child	3.6044	10.8132	108.1321	1441.8	21 626
One-year-old child	2.799	8.399	83.99	1120	16 800

Table 5. Induced current density in various body models by 1 μT external magnetic field which is perpendicular to the side of the body $B_0//b$.

Body models	J_{max} [μA/m^2/(μT)]				
	50 Hz	100 Hz	1 kHz	10 kHz	100 kHz
Average man	3.103	9.309	93.09	1241.3	18620
Ten-year-old child	2.42	7.258	72.58	967.8	14517
Five-year-old child	2.135	6.405	64.05	854.1	12 812
One-year-old child	2.06	6.02	61.99	826.6	12 399

Table 6. Induced current density in body models by 1 μT external magnetic field which is vertical to the body $B_0//a$.

Body models	J_{max} [μA/m²/(μT)]				
	50 Hz	100 Hz	1 kHz	10 kHz	100 kHz
Average man	2.513	7.54	75.4	1005.3	15 080
Ten-year-old child	1.88	5.665	56.656	755.4	11 331
Five-year-old child	1.63	4.887	48.87	651.6	9774
One-year-old child	1.412	4.237	42.37	565	8475

Table 7. Induced current density in body models by 1 μT external magnetic field which is perpendicular to front of the body.

Body models	J_{rms} [μA/m²/(μT)]				
	50 Hz	100 Hz	1 kHz	10 kHz	100 kHz
Average man	2.743	8.23	82.3	1097.2	16 458
Ten-year-old child	1.967	5.9	59.018	786.9	118 004
Five-year-old child	1.648	4.945	49.45	659.4	9812
One-year-old child	1.3	3.878	38.78	517.113	7756.7

axis of the body), induced current density to the body is less than other field-body configurations ($B_0//b$ and $B_0//c$). As a result, induced current density may vary with shape and size of the body, exposure frequency and the orientation of the body relative to the field. Figure 2 and Tables 3–7 summarises the current densities in children's and adults' body when they are subject to external electric and magnetic fields. It is also easy to compare the exposures for field orientations. At exposure frequency, the induced current density varies in relation to the field orientation and the body models. The size and the shape of the body as well as the field orientation are the major parameters for induced current prediction.

The band of frequencies chosen for this study was between 50 Hz and 100 kHz. In this way, the densities of electrical currents induced in the body models of children and adults by the magnetic fields caused by the power frequencies and the frequencies contained in transient sparks were investigated. Transient fields may contain all three components of the magnetic field as well as at least one of the components of the electric field. In residential homes, these magnetic fields affect all the people living within. In bedrooms, these components of the fields may be parallel as well as perpendicular to the children's beds. The analysis indicates that the maximum induced current density occurs when the electric field component is parallel to the major axis of the body. In contrast, the induction of highest current density occurs when the external magnetic field component is parallel to the minor axis of the body. The results show that the transient electric and magnetic fields would induce higher current density in the child body than power frequency fields with similar field strength.

At this point it should be mentioned that frequency of external field appears to be an important parameter of the exposure as the induced current density increases with the frequency. Therefore the transients are of particular interest because they would induce higher current density in child body than power frequency fields with similar field strength. Induced current values of 75 and 100 nA/cm² were found on chest and abdominal areas of the anatomical man model (ungrounded), respectively, in the measurements which were performed at 60 Hz, 10 kV/m[25]. Calculated values of current densities in this study, 72.2 nA cm^{-2} in 50 Hz, 10 000 V/m (Table 3), are in good agreement with measured values.

Although the main aim of this study is not comparison of induced current densities with safety guidelines, current densities induced by 1 μT magnetic field and 1 V/m electric field stay under the basic ICNIRP restrictions.

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