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A New Method to Estimate the Induced Electric Field in the Human Child Exposed to a 100 kHz-10 MHz Magnetic Field Using Body Size Parameters

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In this paper, a new and simple method is proposed to quickly estimate the induced electric field in the human child exposed to a 100 kHz-10 MHz magnetic field, for the sake of electromagnetic field (EMF) safety assessment. The quasi-static finite-difference time-domain (FDTD) method is used to calculate the induced electric fields in high resolution 3D human child models with various body size parameters, in order to derive the correction factor for the estimation equation. The calculations are repeated for various frequencies and incident angles of the magnetic field. Based on these calculation results, a new and simple estimation equation for the 99th percentile value of the body electric field is derived that depends on the body size parameters, and the incident magnetic field. The estimation errors were equal to or less than 5.1%, for all cases considered.

Keywords : dosimetry, finite difference methods, induced electric field, magnetic field exposure

1. Introduction

For many decades, the advances in electric and electronic engineering have improved the quality of our lives. In recent years, however, the proliferation of mobile devices, wearable devices, and emergence of technologies like RFID and wireless power transfer (WPT) have increased the potential human exposure to electric, magnetic, and electromagnetic fields (EMF). When the human body is exposed to a magnetic field, the corresponding induced electric field can cause harmful effects, such as direct stimulation of nerve and muscle tissues [1]. Because of this, the international standards and guidelines (IEEE and ICNIRP) that protect humans from electromagnetic fields have set certain values of induced electric field as basic restrictions [1, 2]. The basic restrictions are physical quantities that are based on established health effects, and that should not be exceeded.

However, despite the necessity to use the induced electric field as a gauge to assess the safety of the human body exposed to magnetic fields, it is not practical to measure the induced electric field in the human body, because of the difficulties associated with placing probes in the human body. Thus, numerical methods, such as the scalar potential finite-difference (SPFD) method [3], impedance method [4], or quasi-static finite-difference time-domain (FDTD) method [5, 6], have been used to calculate the induced electric field, or induced current, in the 3D human models.

Even though these numerical methods can provide detailed distributions of the induced electric field in the human body, and various insights associated with those, such as the maximum and average value of electric field in different biological tissues, these calculations require the use of highly sophisticated computer software, extensive knowledge of numerical techniques, and considerable computing power. Moreover, the calculation results strictly depend on the types and sizes of the human models used. In other words, if the body size parameters of the actual person exposed to the magnetic field are different from those of the human models analyzed, the calculation result will not accurately represent the actual induced electric field in the person. This can be particularly problematic for the safety assessment of children, whose body size parameters can vary over a wide range. Thus, for the safety assessment of children exposed to a magnetic field, a simple estimation method of the induced electric field is needed that only requires the body size parameters, without 3D human models.

In this paper, a new estimation equation is presented,

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based on Faraday's law and a rectangular loop approximation, to quickly estimate the 99th percentile value of induced electric field (E_{99}) in the human child exposed to a 100 kHz-10 MHz magnetic field. In order to derive the correction factor for the proposed estimation equation, induced electric fields in high-resolution 3D human child models are calculated, using the quasi-static FDTD. These calculations are repeated for various frequencies and incident directions of the magnetic field, for children models with different gender, age, and body size parameters. Then, the effect of exposure parameters and children models on the induced electric field is analyzed. Based on these calculation results, a correction factor is derived for two directions of the incident magnetic field. This correction factor is used to reduce error, when a complex and nonhomogeneous human body is approximated as a simple rectangular loop in order to apply Faraday's law. The proposed estimation equation is very simple to use, and only depends on the frequency and magnitude of the magnetic field, and the body size parameters of the exposed child. The estimation errors are analyzed, to verify the proposed method.

2. Calculation of the Induced Electric Field in the Child Models

In this chapter, the quasi-static FDTD method [5, 6] is applied to the induced electric field calculation of human child models. Human child models with different gender and body sizes are analyzed and compared. The frequency range considered is 100 kHz-10 MHz, which is also the frequency range of the resonant WPT systems.

2.1. Three-dimensional high-resolution human children models

Six children models are analyzed for the induced electric field calculation. The models are included in the Virtual Population models provided by Information Technologies in Society (IT'IS) [7]. Virtual Population is based on the full body MRI data of volunteers, and human tissues and organs are represented by 3-dimensional CAD data (Fig. 1). The children models consist of 3 male and 3 female models. They have different body parameters, which are summarized in Table 1. 5 mm voxels are used for voxel size. Using convergence analysis, it was shown that 5 mm voxel models are adequate for the EMF safety assessment using the 99th percentile value of the electric field (E_{99}) [6]. The total number of voxels was about 133,000 for the smallest "Roberta" model, and about 377,000 for the biggest "Louis" model.

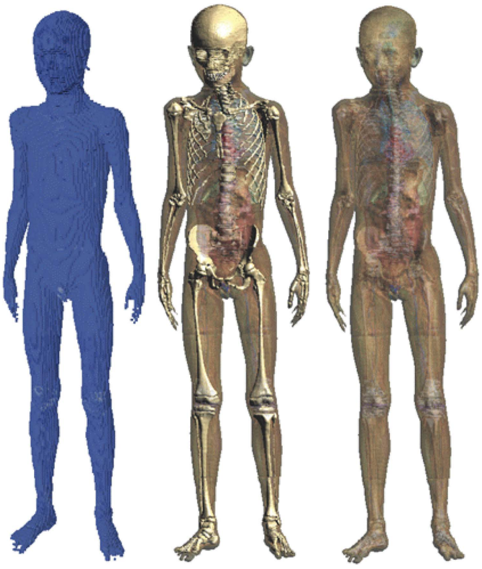


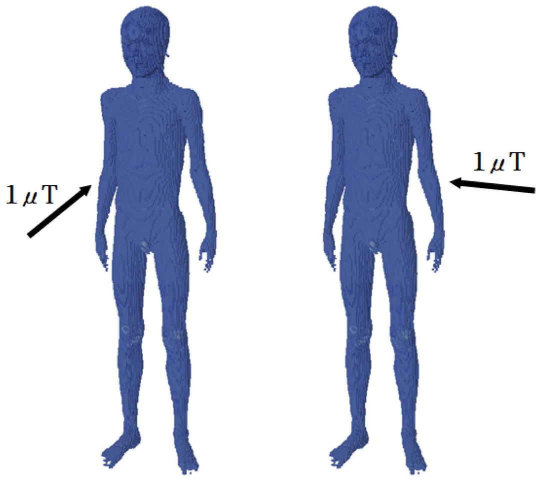
Fig. 1. (Color online) The shape and internal tissues of the Virtual Population "Dizzy" model (8 year old boy).

2.2. Calculation results of the induced electric field

For the calculation of the induced electric field, the children models are exposed to magnetic fields, according to the following conditions. 100 kHz-10 MHz frequency range is considered, which is what is used for the resonant WPT system. From 100 kHz to 1 MHz, the frequency points are increased by 100 kHz. From 1 MHz to 10 MHz, the frequency points are increased by 1 MHz. For all the cases, the magnitude of the magnetic field was set as 1 μT. Two types of incident directions are considered (Fig. 2). In the "F2B (Front-to-Back)" case, the magnetic field points from the front of the person to the back; and in the "S2S (Side-to-Side)" case, the magnetic field points from

Table 1. Virtual Population model data.

Name	Louis	Billie	Eartha	Dizzy	Thelonious	Roberta
gender	male	female	female	male	male	female
age [year]	14	11	8	8	6	5
height [m]	1.69	1.47	1.36	1.40	1.17	1.09
weight [kg]	50.4	35.4	30.7	26.0	19.3	17.8
BMI [kg/m^2]	17.7	16.5	16.7	13.4	14.0	14.9
number of tissues	77	75	75	66	76	66

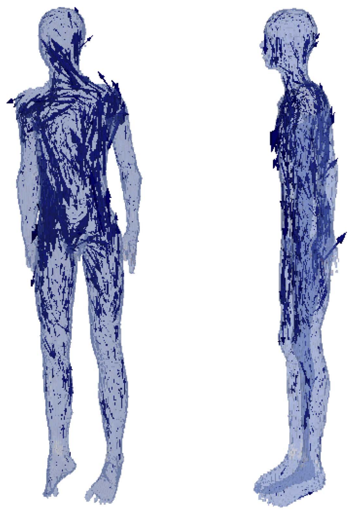


(a) (b)

Fig. 2. (Color online) The directions and the magnitude of the magnetic field exposure considered. (a) F2B (Front-to-Back), and (b) S2S (Side-to-Side).

the left side of the person to the right side. For the grounding condition, the “no ground” condition was used, where the two feet of the models are in the air, and are not in direct contact with the ground plane. The “no ground” condition was found to yield higher induced electric field in the upper body, in some of the magnetic field exposure conditions considered in [6], since when both feet are grounded, the induced electric field in the upper body diffuses to the lower body.

Fig. 3 shows the three-dimensional distribution of the induced electric field for different magnetic field directions of incidence. It can be seen that most of the electric fields are concentrated around the perimeter of the body, with respect to the cross-section normal to the direction of incidence. Qualitatively, these results agree well with Faraday’s law, and the use of Faraday’s law as a basis of the induced electric field estimation can be justified. However, for quantitatively accurate estimation, a correction factor must be considered, which will be introduced in the next chapter.



(a) (b)

Fig. 3. (Color online) 3D distribution of induced electric field for “Louis” model at 1 MHz. (a) F2B exposure, and (b) S2S exposure.

Figs. 4 and 5 show the 99th percentile value of the induced electric field in the whole body (E_{99}), according to the frequency of the magnetic field for F2B and S2S exposures, respectively. The 99th percentile value is the top 1% value, when all the electric field values in the whole body voxels are sorted in descending order. It can be seen that the E_{99} value is the lowest at 100 kHz, and increases almost linearly, according to the frequency.

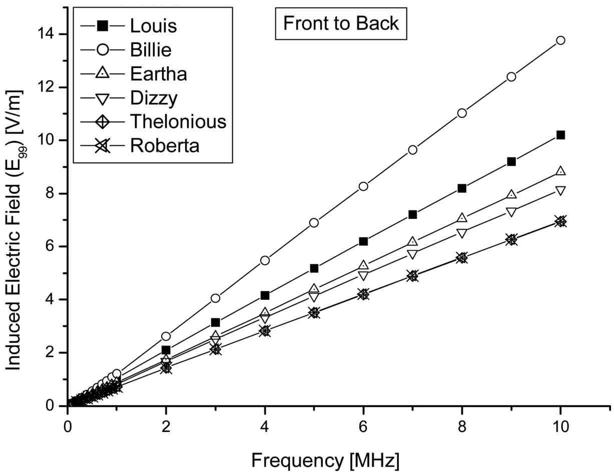


Fig. 4. Induced electric field (E_{99}), according to the frequency change (F2B exposure).

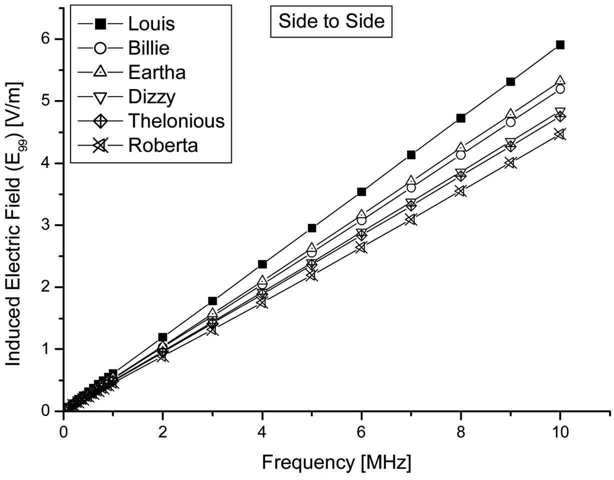


Fig. 5. Induced electric field (E_{99}), according to the frequency change (S2S exposure).

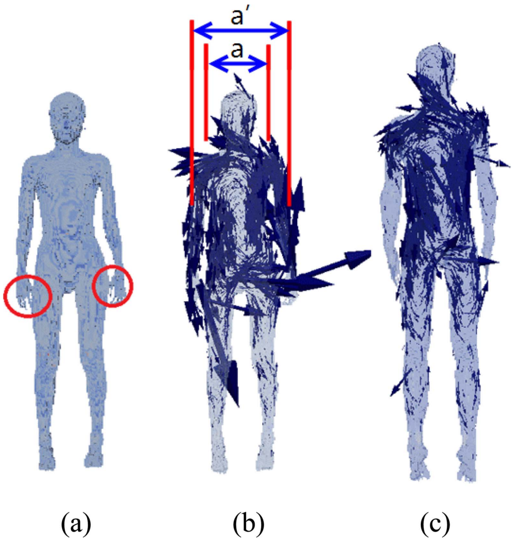


Fig. 6. (Color online) Comparison of the induced electric field distribution of the "Billie" and "Louis" models. (a) "Billie" model shown with the hands in contact with the torso; (b) Induced electric field distribution of the "Billie" model, and definition of body size parameters *a* and *a*′ (F2B exposure); and (c) Induced electric field distribution of the "Louis" model (F2B exposure).

These results also agree well with Faradays' law, and they form the basis of the estimation equation for the E_{99} values. The minimum value was 0.0494 V/m at 100 kHz for the "Roberta" model under S2S incidence, and the maximum value was 13.7592 V/m at 10 MHz for the "Billie" model under F2B incidence.

These results show that in general, the children models with bigger body size parameters have higher induced electric field. In other words, persons with higher cross-sectional area with respect to the magnetic field exposure will have a higher induced electric field. The estimation method for E_{99} will incorporate this relationship between body size parameters and induced electric field, using a rectangular loop approximation.

However, Fig. 4 shows some exceptions to this rule, which need to be further investigated here. Table 1 shows that the "Louis" model has the biggest body size. However, for F2B exposure at 10 MHz, the "Billie" model, which has a smaller body size, had a higher E_{99} value of 13.7592 V/m, compared to 10.1955 V/m of the "Louis" model. Further investigations show that unlike other models, the hand of the "Billie" model was in contact with the torso, resulting in bigger loops for the induced electric field, including the arms (Fig. 6). Figs. 7-8 compare the E_{99} values of the representative tissues (organs) in the "Billie" and "Louis" models. The E_{99} values of organs inside the torso, such as the lung, kidney and stomach, do not show much discrepancy. However, for tissues like skin, bone, fat and muscle, which are located near the outside perimeter of the body, the E_{99} values of "Billie" model are considerably higher than those of the "Louis" model, because of the bigger loop resulting from the contact of the hand and the torso.

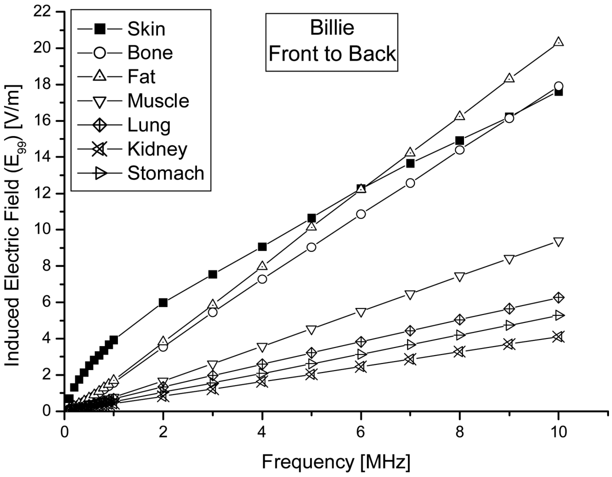


Fig. 7. 99th percentile value of the induced electric field (E_{99}), in various tissues of the "Billie" model (F2B exposure).

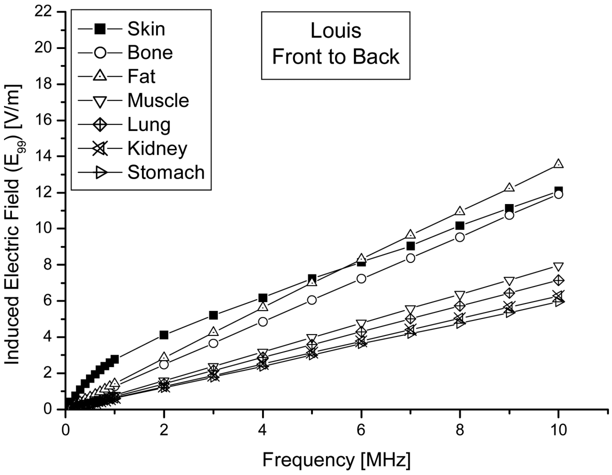


Fig. 8. 99th percentile value of the induced electric field (E_{99}), in various tissues of the "Louis" model (F2B exposure).

3. Estimation of the Induced Electric Field

As can be seen from Fig. 3, the induced electric field in the human model due to magnetic field exposure forms a large loop along perimeters of the torso, as predicted by Faraday's law. Accordingly, one natural method of estimating the induced electric field in the human body is to approximate the human body as a circular or rectangular loop, and directly apply Faraday's law. In the 1998 ICNIRP

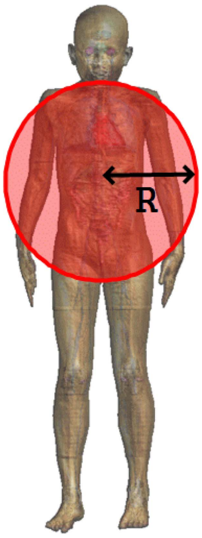
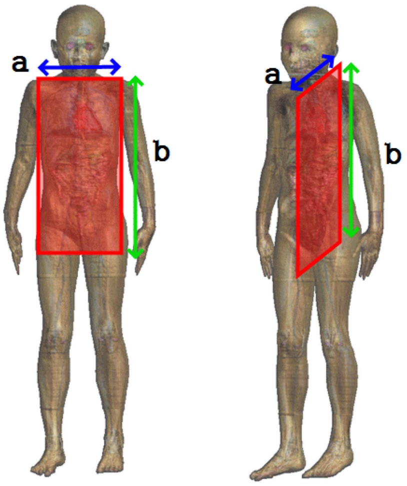


Fig. 9. (Color online) A circular loop approximation of the child model ("Eartha" model).



(a) (b)

Fig. 10. (Color online) A rectangular approximation of the child model, and definition of body size parameters ("Eartha" model). (a) F2B exposure, and (b) S2S exposure.

guideline [8], assuming a homogeneous and isotropic body, and a sinusoidal wave, the simple estimation equation for the induced current J using the circular loop approximation (Fig. 9) is given as,

$$J = \pi R f \sigma B \tag{1}$$

where, B is the magnetic flux density with frequency f, σ is the electrical conductivity of the loop, and R is the radius of the loop. Since $J = \sigma E$, it follows that the induced electric field E is given as,

$$E = \pi R f B \tag{2}$$

However, it is difficult to apply (1) or (2) to practical situations, since setting the radius of the loop R from the human model is arbitrary, and introduces large errors.

One other alternative to (2) is to use a rectangular loop approximation, which yields

$$E = \left(\frac{ab}{a+b}\right)\pi f B \tag{3}$$

where, a and b are the width and height of the loop, respectively. The loop sizes a and b can be measured from the human models, or actual persons. For F2B exposure, a is measured as the distance between two axillas, and b is measured from the top of the shoulder to the bottom of the pelvis. For S2S exposure, a is measured from the front of the chest to the furthest point on the back; and b is the same as the F2B case (Fig. 10). The body size parameters measured from six children models are summarized in Table 2.

Using this approximation, the size of the rectangular loop can be clearly defined for any human model or actual person, and the induced electric field can be estimated using (3). However, because of the irregular shape and inhomogeneous tissues of the actual human body, the simple approximation equation (3) also yields considerable errors.

Thus, we introduce a dimensionless correction factor k that can take into account the irregular shape and inhomogeneous tissues of actual humans. Using the correction factor k, a new estimation equation for E_{99} is given by,

$$E_{99_{\mathrm{est}}} = k\left(\frac{ab}{a+b}\right)\pi f B \tag{4}$$

Assuming that the calculated value of $E_{99_{\mathrm{FDTD}}}$ using quasi-static FDTD is the same as the estimated value $E_{99_{\mathrm{est}}}$, the correction factor can be calculated as,

$$k = \left(\frac{ab}{a+b}\right)\frac{E_{99_{\mathrm{FDTD}}}}{\pi f B} \tag{5}$$

Table 2. The body size parameters for rectangular loop approximation (unit: mm).

Name	Louis	Billie	Eartha	Dizzy	Thelonious	Roberta
a (F2B exposure)	261	227	220	218	189	185
a (S2S exposure)	170	155	142	138	142	125
b	591	547	506	512	432	409

Using (5), the correction factor k is calculated for 6 child models exposed to a 100 kHz-10 MHz magnetic field, and the average value of k is taken to be the representative correction factor for children between 5 to 14 years old.

Table 3 summarizes correction factors k, averaged over the 100 kHz-10 MHz frequency range for each child model. Despite the fact that all models have different body size parameters, the correction factor shows good consistency. For F2B exposure, k values were all within the 1.718-1.827 range, except for the "Billie" model. For the "Billie" model, as was explained in Chapter 3, because the hand is in contact with the torso, the loop for induced current and electric field includes both arms, which results in a wider loop than other child models. Thus, for the "Billie" model, the body size parameter a should be changed to a', which is measured for the full body width (Fig. 6(b)). Using the new loop width a', the correction factor k for the "Billie" model is calculated as 1.741, which is within the same range as for the other child models. The average value of all 6 models, k_{avg} was 1.771 for F2B exposure. For S2S exposure, the k values were within 1.413-1.551 for all models considered, and the average value k_{avg} was 1.478.

Using (4) and the average value of the correction factor k_{avg} in Table 3, the E_{99} value of the induced electric field in the child with arbitrary body size parameters can be easily estimated. The conditions under which (4) can be applied are: (a) the child's age is between 5 and 14, (b) the magnetic field frequency is within the 100 kHz-10 MHz range, and (c) the magnetic field direction of incidence is either F2B or S2S, as defined in Fig. 2. Under these conditions, (4) will give a reasonable estimation of E_{99} value in the child.

Tables 4 and 5 compare the 99th percentile value of the full body induced electric field calculated by quasi-static FDTD ($E_{99_{\mathrm{FDTD}}}$), with those estimated by (4) ($E_{99_{\mathrm{est}}}$), for 1 MHz magnetic field exposure. For all models, the errors were within 5%, except for the "Billie" model with S2S exposure, of which the error is around 5.1%. These results show the validity of the proposed estimation method.

4. Conclusion

In this paper, a new estimation equation for the induced electric field in the human child exposed to 100 kHz-10 MHz magnetic field was proposed, based on the rectangular loop approximation. To calculate the correction factor k with consideration of the irregular shape and inhomogeneous tissues of the actual human child, induced electric fields in high-resolution, 3D child models with different body size parameters were analyzed, using quasi-static FDTD for 100 kHz-10 MHz magnetic field exposure. For all six children models considered, the correction factor values that were obtained based on the numerical analysis showed good consistency, despite their different body sizes. When the average value of k was taken as a representative value, the estimation errors were less than 5% for all models and cases considered, except one, showing the validity of the proposed method.

Since the average correction factor k_{avg} is established, this estimation method can be easily applied to children

Table 3. Calculated values of the correction factor k for each model.

Name	Louis	Billie	Eartha	Dizzy	Thelonious	Roberta	k_{avg}
k (F2B exposure)	1.827	1.742*	1.824	1.718	1.740	1.777	1.771
k (S2S exposure)	1.466	1.414	1.551	1.457	1.455	1.525	1.478

*For the "Billie" model F2B exposure, k is recalculated using a' in Fig. 6 (b) as the width of the rectangular loop.

Table 4. Comparison of $E_{99_{\mathrm{FDTD}}}$ and $E_{99_{\mathrm{est}}}$ for 1 MHz, F2B exposure.

Name	Louis	Billie	Eartha	Dizzy	Thelonious	Roberta
$E_{99_{\mathrm{FDTD}}}$ [V/m]	1.051	1.214	0.876	0.827	0.724	0.720
$E_{99_{\mathrm{est}}}$ [V/m]	1.007	1.257	0.853	0.851	0.732	0.709
Error [%]	−4.119	+3.596	−2.579	+2.853	+1.050	−1.554

Table 5. Comparison of $E_{99_{\mathrm{FDTD}}}$ and $E_{99_{\mathrm{est}}}$ for 1 MHz, S2S exposure.

Name	Louis	Billie	Eartha	Dizzy	Thelonious	Roberta
$E_{99_{\mathrm{FDTD}}}$ [V/m]	0.609	0.534	0.536	0.496	0.488	0.457
$E_{99_{\mathrm{est}}}$ [V/m]	0.613	0.561	0.515	0.505	0.496	0.445
Error [%]	+0.637	+5.077	−3.974	+1.721	+1.799	−2.801

with various body size parameters, without complex numerical analysis. It is anticipated that this method will be widely used for estimating the basic restriction (induced electric field) of a child exposed to a 100 kHz-10 MHz magnetic field.

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References

[1] International Commission on Non-Ionizing Radiation Protection, Health Physics **99**, 818 (2010).

[2] IEEE Standard C95.1-2005, IEEE, New York (2006) pp. 14-15.

[3] T. W. Dawson, J. De Moerloose, and M. A. Stuchly, Appl. Comput. Electromagn. Soc. J. **11**, 63 (1996).

[4] O. P. Gandhi, G. Kang, D. Wu, and G. Lazzi, Bioelectromagnetics **22**, 112 (2001).

[5] J. De Moerloose, T. W. Dawson, and M. A. Stuchly, Radio Science **32**, 329 (1997).

[6] H.-J. Song, H. Shin, H.-B. Lee, J.-H. Yoon, and J.-K. Byun, IEEE Trans. Magn. **50**, 7025804 (2014).

[7] A. Christ, W. Kainz, E.G. Hahn, K. Honegger, M. Zefferer, E. Neufeld, W. Rascher, R. Janka, W. Bautz, J. Chen, B. Kiefer, P. Schmitt, H.-P. Hollenbach, J. Shen, M. Oberle, D. Szczerba, A. Kam, J. W. Guag, and N. Kuster, Phys. Med. Biol. **55**, 23 (2010).

[8] International Commission on Non-Ionizing Radiation Protection, Health Physics **74**, 494 (1998).