ISSN (Print) 1226-1750
ISSN (Online) 2233-6656
Journal of Magnetics 23(3), 473-479 (2018) https://doi.org/10.4283/JMAG.2018.23.3.473

The Human Exposure Assessment of Magnetic Field From an Induction Cooktop Using Coupling Factor Based on Measurement Data

Kyu-Jin Jung and Jin-Kyu Byun*

Department of Electrical Engineering, Soongsil University, Seoul 06978, Republic of Korea

(Received 31 July 2018, Received in final form 10 September 2018, Accepted 10 September 2018)

In this paper, the human exposure to the magnetic field from a household induction cooktop is assessed using two different methods. For the first method, the magnetic field from an induction cooktop is measured and compared with the reference levels (RLs) in the EMF (electromagnetic fields) guidelines. For the second method, coupling factors are calculated by simulations of 3-D human models and equivalent sources according to the IEC 62311 standard. The equivalent sources are obtained based on the non-uniform spatial distribution of the measured magnetic fields. Using the coupling factor, the induced current density and electric field inside the human body are estimated, and compared with basic restrictions (BRs) in the EMF guidelines. The exposure indices are calculated for both methods and the results are compared. Also, the possibility of overestimation is investigated when the measured magnetic field is compared with the reference levels.

Keywords : coupling factor, exposure assessment, induction cooktop, magnetic field measurement

1. Introduction

Nowadays, household induction cooktops are widely used and becoming more and more popular because of their high efficiency, safety, ease of use, and fast heating [1]. Since they are used almost every day close to the human body, it is becoming increasingly important to properly and accurately assess the human exposure to magnetic field from induction cooktops.

International organizations such as ICNIRP (international commission on non-ionizing radiation protection) and IEEE have established EMF (electromagnetic fields) protection guidelines that define exposure limits [2-4]. Generally, these exposure limits fall into one of the two categories. The first category is called the basic restrictions (BRs), which are derived based on established health effects such as electrostimulation and heating. In the frequency range below 10 MHz, they are defined in terms of induced current density or internal electric field in the human body. They also include some safety factors for extra protection.

The second category is called the reference levels (RLs), defined in terms of electric or magnetic field in free space. Since BRs are difficult to measure, RLs are provided for practical exposure assessment purposes. However, RLs are derived from conservative estimates of BRs assuming uniform field exposure conditions. Thus, when assessing the human exposure to non-uniform field sources such as induction cooktops, measuring magnetic field in free space and comparing it with RL can lead to overestimation of the actual exposure. To overcome this problem, the IEC 62311 standard proposes exposure assessment method for non-uniform magnetic field sources based on calculation of coupling factor K [5].

In this paper, the human exposure to the magnetic field from a household induction cooktop is assessed using two different methods. For the first method, the magnetic field from an induction cooktop is measured and compared with the RLs in the EMF guidelines. For the second method, coupling factors are calculated by simulations of the 3-D human models and equivalent sources according to the IEC 62311 standard. The equivalent sources are obtained based on the spatial distribution of the measured magnetic fields. Using the coupling factor, the induced current density and internal electric field in the human body are estimated, and compared with BRs in the EMF guidelines. The exposure indices are calculated for both assessment methods.

*Corresponding author: Tel: +82-2-820-0644
Fax: +82-2-817-7961, e-mail: jkbyun@ssu.ac.kr

2. Exposure Assessment using Reference Levels

2.1. Measurement of magnetic field from induction cooktop

In this section, the magnetic field from a commercial household induction cooktop from company A is measured. A stainless pot filled with 800 ml of water is placed on the cooktop as a thermal load. Without a thermal load, the cooktop does not operate properly. In order to keep the experiment conditions as close as possible between measurements, the water in the pot was regularly refilled to maintain the water level and temperature. The specifications of the induction cooktop and the stainless pot are shown in Table 1. EHP-200 model from Narda Safety Test Solutions is used as a probe, which can measure the electric field and magnetic field up to the frequency of 30 MHz. For one probe position, the magnetic flux density is measured three times at 2 min 20 sec, 3 min 20 sec, and 4 min 20 sec from the starting time, and the median of three measurement data is used as a representative value of that probe position. The averaging time for the RMS magnetic field is 120 seconds.

The measurement procedure is as follows:

1) The measurements are performed for three values (10, 15, and 20 cm) of horizontal distance *d* shown in Fig. 1 between the probe and the induction cooktop.

2) For each value of *d*, the probe vertical position *h* (Fig. 1) is increased by 2 cm steps to find the maximum magnetic field position.

3) The above steps are repeated for each heating level (8 total), which can be adjusted by the control panel of the induction cooktop.

The maximum value of the magnetic flux density was found at the vertical positions of h = 8, 8, and 10 cm for the horizontal distances of d = 10, 15, and 20 cm, respectively. Fig. 2 shows the measured magnetic field for different heating levels of the induction cooktop and horizontal distance *d*. The maximum value of the magnetic flux density was 5.2 μT at d = 10 cm for heating level 8, and the minimum value was 0.7 μT at d = 20 cm for heating level 1. As expected, the higher heating level and the closer distance *d* resulted in the higher value of the magnetic flux density.

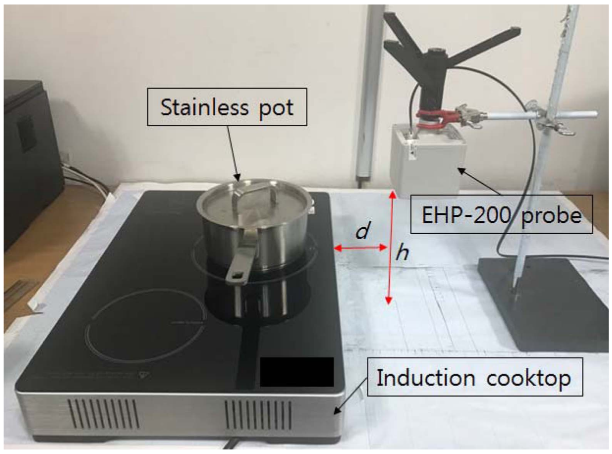


Fig. 1. (Color online) The setup for the induction cooktop magnetic field measurement.

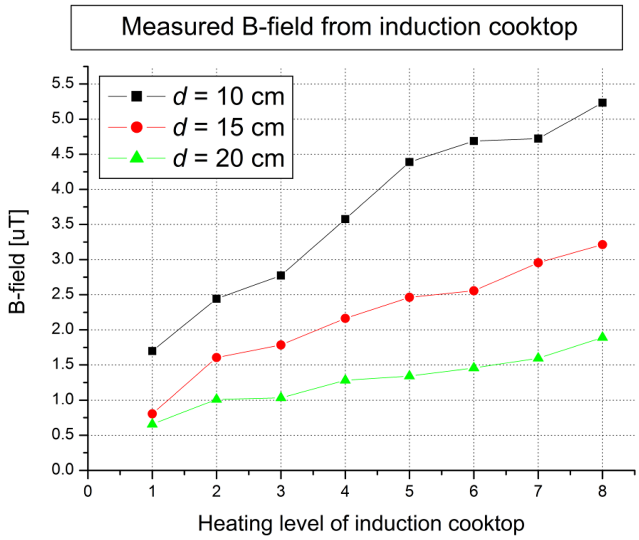


Fig. 2. (Color online) The measured magnetic flux density from the induction cooktop for different heating levels and horizontal distances.

2.2. Exposure indices with respect to reference levels in EMF guidelines

In this section, the exposure indices are calculated with respect to the reference levels in EMF guidelines. The

Table 1. The specifications of the induction cooktop and the stainless pot.

Induction cooktop		Stainless pot	
Rated voltage	220 [V], 60 [Hz]	Material	Surface layer : stainless steel 18/10 Inner layer : aluminum
Power consumption [W]	2000	Size [cm]	Diameter : 16 Height : 8.5

Table 2. Basic restriction and reference level exposure limits for general public at 28 kHz in ICNIRP 1998 and 2010 guidelines [2, 3].

ICNIRP 1998			ICNIRP 2010		
Frequency	Induced current density (basic restrictions) [mA/m^2]	B-field (reference level) [μT]	Frequency	Internal electric field (basic restrictions) [V/m]	B-field (reference level) [μT]
28 kHz	56	6.25	28 kHz	3.78	27

analysis of the frequency spectrum of the measurement data reveals that the fundamental frequency of the magnetic field from the induction cooktop is 28 kHz, which coincides with the switching frequency of the induction cooktop coil driver circuit. The basic restriction and reference level exposure limits for general public at 28 kHz are listed in Table 2 for ICNIRP 1998 and 2010 guidelines [2, 3].

In order to evaluate the EMF exposure from the induction cooktop, the exposure index is used. For electrical stimulation effects below 10 MHz, the exposure index is defined as a ratio of the measured or calculated BR or RL value divided by the corresponding exposure limit [2]. For example, in this paper, the exposure index for the magnetic flux density EI_B is defined as:

$$EI_B = \frac{B_{\max}}{B_{\text{limit}}} \times 100\,[\%] \tag{1}$$

where B_{max} is the maximum value of the measured magnetic flux density, and B_{limit} is the exposure limit at the field frequency. Table 3 summarizes the calculated exposure indices for the magnetic flux density at the horizontal distance d = 10 cm. Fig. 3 shows exposure indices with respect to ICNIRP 1998 guideline for d = 10, 15, and 20 cm.

B_{limit} value of ICNIRP 1998 (6.25 μT) is lower than that of ICNIRP 2010 (27 μT), which means ICNIRP 1998 is the stricter guideline of the two. As a result, EI_B value with respect to ICNIRP 1998 is higher than that obtained with respect to ICNIRP 2010. Even though the exposure indices do not exceed 100 % for all cases considered, EI_B value with respect to ICNIRP 1998 is about 83 % for maximum heating level at d = 10 cm. These results may raise concern about the possibility that the magnetic field from the induction cooktop may exceed reference levels of ICNIRP 1998 guideline at distances shorter than 10 cm. However, as mentioned in the previous chapter, exposure indices with respect to the reference levels can lead to overestimation of the actual exposure when dealing with non-uniform field sources such as induction cooktops [2, 4]. Therefore, another exposure assessment method is investigated in the next chapter which estimates induced current density and electric field in the human body by using coupling factor.

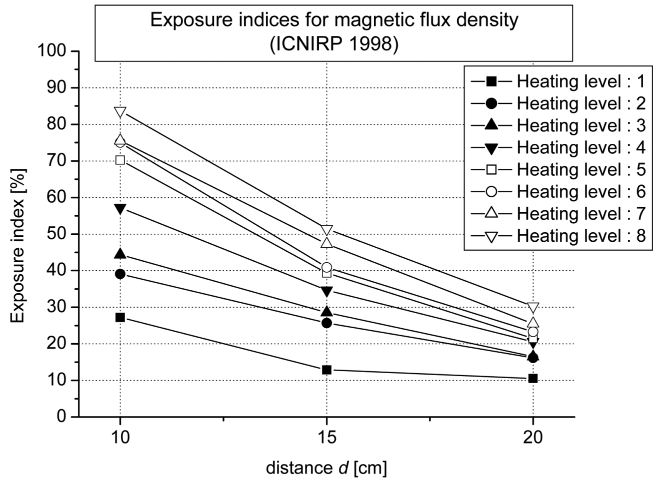


Fig. 3. Magnetic flux density exposure indices (EI_B) with respect to reference level of ICNIRP 1998 guideline.

Table 3. The exposure indices for magnetic flux density (EI_B) with respect to the reference levels in ICNIRP 1998 and 2010 guidelines at d = 10 cm.

ICNIRP 1998		ICNIRP 2010	
Heating level	EI_B [%]	Heating level	EI_B [%]
1	27.1856	1	6.2930
2	39.0928	2	9.0493
3	44.3776	3	10.2726
4	57.2176	4	13.2448
5	70.2288	5	16.2567
6	75.0240	6	17.3667
7	75.5664	7	17.4922
8	83.7280	8	19.3815

3. Exposure Assessment Based on Coupling Factor K

In this chapter, exposure assessment of induction cooktop using coupling factor K is investigated. Coupling factors are calculated by simulations of 3-D human models and equivalent sources according to the IEC 62311 standard [5]. The equivalent sources are obtained based on the spatial distribution of the measured magnetic fields. Using the coupling factor, the induced current density and internal electric field in the human body are estimated, and the exposure indices are calculated with respect to the BRs in EMF guidelines.

3.1. Determination of the equivalent coil parameters

The calculation of coupling factor K requires the induced current density and electric field values inside the human body, which are difficult to measure. Thus, they are obtained by simulations of human models and equivalent sources. Since the specification of the coil inside the induction cooktop is unknown, equivalent sources are derived in the form of the circular coils that produce magnetic field distribution similar to that of the measurement data. The procedures to determine the equivalent sources are as follows [5]:

1) Three cases are considered for horizontal distances (d = 10, 15, 20 cm).

2) For each value of d, the probe vertical position h (Fig. 1) is increased by 2 cm steps.

3) When the maximum magnetic field B_{max} is found, the vertical position of the maximum field is set as the origin of the hot spot with $r_0 = 0$ (Fig. 4).

4) Step 2) is repeated until the measured magnetic field value falls below 10 % of the maximum field value B_{max}.

5) A normalized integration of the measured magnetic field along the r_0 axis results in a single value G (Fig. 5a), which can be defined as:

$$G(r_{coil}, d_{coil}) = \int_{r_0=0}^{r_0=X} \frac{B(r_0)}{B(r_0=0)} dr_0 \qquad (2)$$

6) The G value obtained from measurement results are used to determine the parameters (r_{coil} and d_{coil}) of an equivalent circular coil (Fig. 5b) that gives a similar area G_{eq} in Table 4. The values in Table 4 are given by analytic calculations [5].

7) If there is no value in Table 4 that exactly matches the measurement result G, d_{coil} for the closest G_{eq} value is taken. Then, r_{coil} is determined by interpolating the neigh-

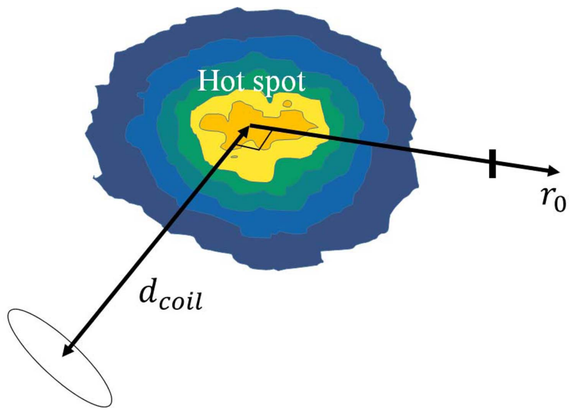


Fig. 4. (Color online) Magnetic field hot spot from the equivalent circular source coil [5].

Table 4. Area G_{eq} [m] of equivalent coils for different values of r_{coil} and d_{coil} [5].

Distance d_{coil} (mm)	Radius r_{coil} (mm) 10	20	30	50	70	100
10	.01354					
15	.01562					
20	.01848	.02703				
25	.02168	.02880				
30	.02511	.03117	.04051			
35	.02861	.03390	.04217			
40	.03222	.03689	.04429			
50	.03955	.04334	.04941	.06750		
70	.05448	.05718	.06164	.07535	.09444	
100	.07711	.07905	.08219	.09213	.10644	.13493
200	.15317	.15415	.15573	.16085	.16845	.18420
300	.22953	.23012	.23119	.23461	.23971	.25054

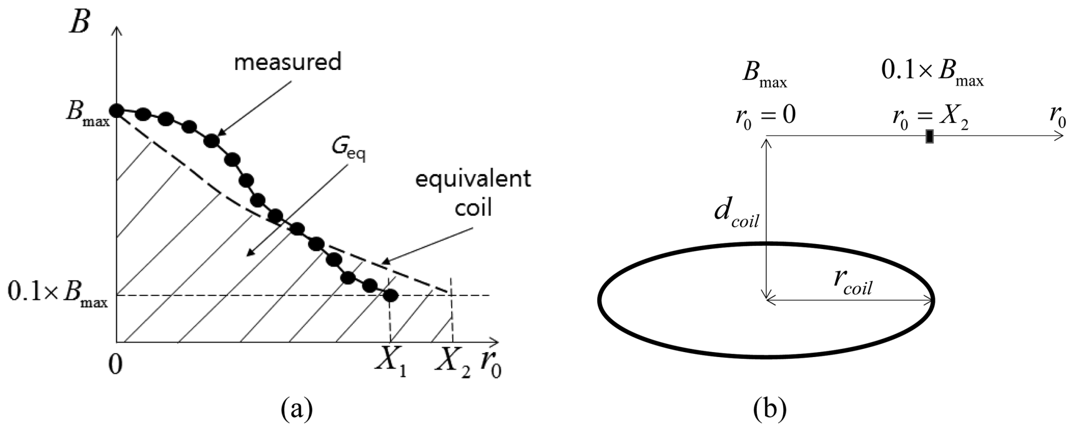
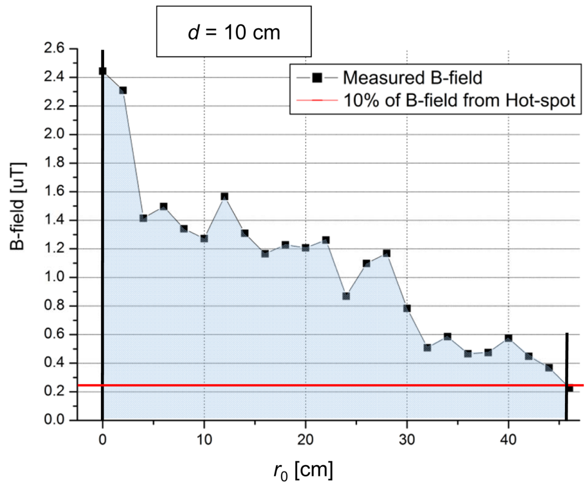
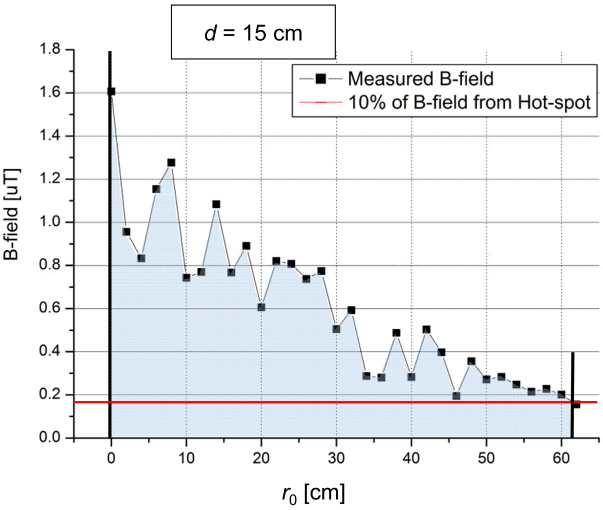


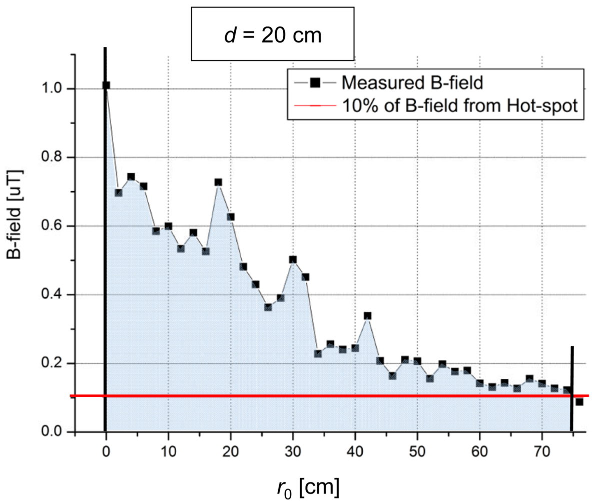
Fig. 5. Magnetic field distribution and equivalent coil. (a) Area G_{eq} and gradients of flux density from measurement and equivalent coil. (b) Parameters of equivalent coil [5].



(a)



(b)



(c)

Fig. 6. (Color online) The area G of the measured B-field distribution from the induction cooktop. (a) d = 10 cm. (b) d = 15 cm. (c) d = 20 cm.

Table 5. Equivalent coil parameters and relative difference between G and G_{eq}.

Distance d [cm]	r_{coil} [mm]	d_{coil} [mm]	Relative difference [%]
10	114.289	200	0.14
15	155	200	0.42
20	121.194	300	0.29

boring values.

Figure 6 shows the area G of the measured magnetic field distribution from the induction cooktop. The equivalent coil parameters r_{coil} and d_{coil} are determined using the procedures described above. Table 5 summarizes the equivalent coil parameters along with the relative differences between area G (measurement) and G_{eq} (equivalent coil).

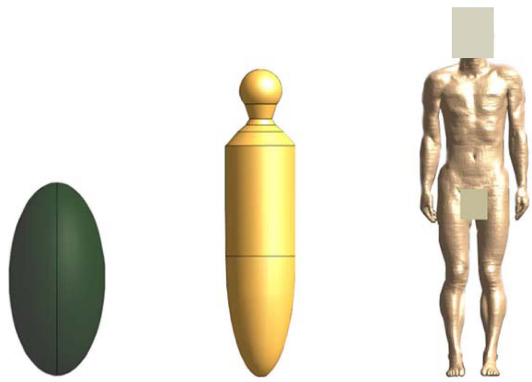
3.2. Human models

In order to calculate the coupling factor, three human models are used with the equivalent sources obtained in the previous section; a prolate spheroid, a simplified human model [5], and an anatomical human model “Duke” from human model software of IT’IS Foundation (Information Technologies in Society) [6-8] (Fig. 7). Table 6 lists the parameters of the three human models. The position of the human models with respect to the equivalent source coils are determined by considering the actual human body position when using the induction cooktop.

3.3. Calculation of coupling factors

Coupling factor K is defined as follows [9-11]:

$$K_{1998} = (J_{max}/B_{max})/(J_{limit}/B_{limit}) \quad (3)$$



(a) (b) (c)

Fig. 7. (Color online) Three equivalent human models used for coupling factor calculations. (a) Prolate spheroid. (b) Simplified human model from IEC 62311 [5]. (c) Anatomical human model “Duke” [6-8].

Table 6. The parameters of the human models.

Human model	Size [cm]	Tissue composition
Prolate spheroid	Height : 80 Width : 40	Homogeneous $\sigma = 0.347$ S/m
Simplified human model from IEC 62311 [5]	Height : 152.8	Homogeneous $\sigma = 0.347$ S/m
Anatomical Human model "Duke" [6-8]	Height : 177	Heterogeneous (74 body tissues)

$$K_{2010} = (E_{max}/B_{max})/(E_{limit}/B_{limit}) \tag{4}$$

where K_{1998} and K_{2010} are the coupling factors normalized by the exposure limits in ICNIRP 1998 and 2010 guidelines, respectively, J_{max}, E_{max}, and B_{max} are the maximum induced current density, electric field, and magnetic flux density in the human model, respectively, and J_{limit}, E_{limit}, and B_{limit} are the exposure limits in the corresponding EMF guidelines, respectively (Table 2). Sim4Life software was used for the EM simulation and calculation of J_{max}, E_{max}, and B_{max} [12].

Figure 8 shows plots of calculated K_{1998} and K_{2010}. In every cases considered, K_{1998} and K_{2010} increase with distance d, since the magnetic field distribution becomes more similar to that of the uniform field with increasing d. Also, the simplified model from IEC 62311 always yields higher coupling factor values than those obtained by the prolate spheroid model. The anatomical model yields the lowest value of K_{1998}, but it yields the highest value of K_{2010} at $d = 15$, 20 cm. This means that the maximum induced electric field E_{max} of the anatomical model is higher than that of the homogeneous models at $d = 15$, 20 cm. This is due to the fact that the conductivity of the tissue where E_{max} is obtained in the anatomical model is different from that of the homogeneous models ($\sigma = 0.347$ S/m).

3.4. Calculation of exposure indices with respect to basic restrictions

Once K_{1998} and K_{2010} are calculated, the exposure indices EI_J and EI_E with respect to the basic restrictions (J and E) in ICNIRP guidelines can be estimated using (1), (3) and (4) as follows:

$$EI_J = K_{1998} \times EI_B \tag{5}$$

$$EI_E = K_{2010} \times EI_B \tag{6}$$

where EI_J and EI_E are the exposure indices with respect to the induced current density J and electric field E, respectively, and EI_B is the exposure index for the magnetic flux density obtained in chapter 2.

Table 7 lists the estimated exposure indices EI_J and EI_E for various heating levels at d = 10 cm. The highest values are EI_J = 29.78 % and EI_E = 1.27 %, respectively, both obtained from the IEC 62311 human model. This is considerably lower than the maximum value of the magnetic field exposure index EI_B = 83.73 % obtained in chapter 2.

EMF guidelines state that the reference level exposure limits are designed to avoid adverse reactions in case of whole body uniform exposure. However, they also state that when a magnetic field is not uniform, which is the case for the induction cooktop, those limits can be overly restrictive [2, 4]. Thus, they allow an acceptable alternative, i.e., to calculate induced current density or electric

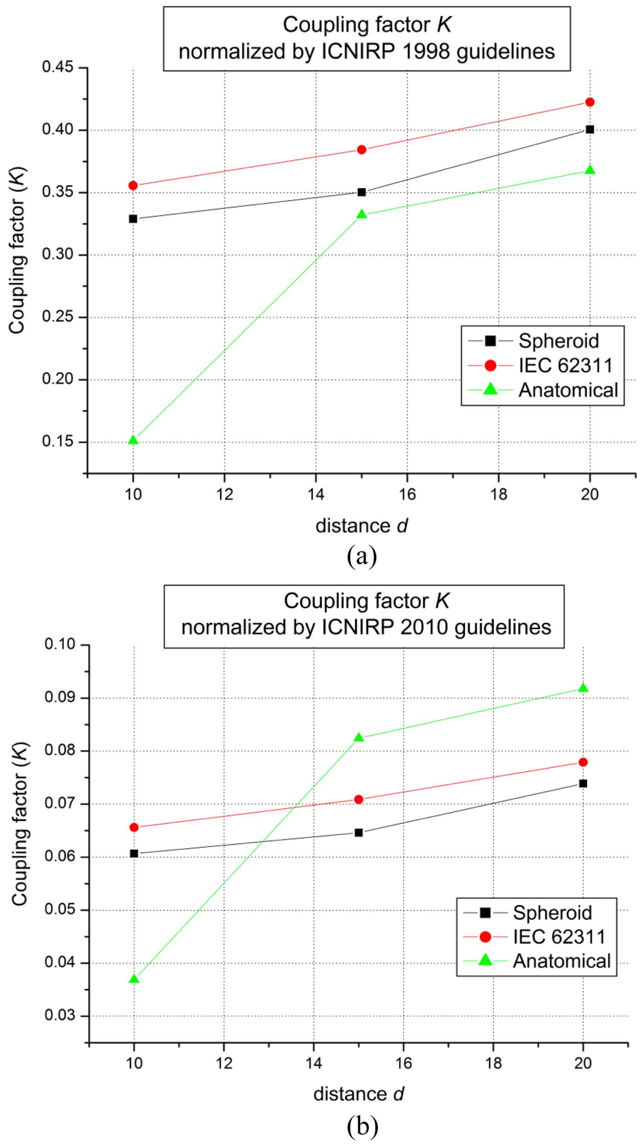


Fig. 8. (Color online) Plots of coupling factor K normalized by exposure limits of ICNIRP 1998 and 2010 guidelines. (a) K_{1998}. (b) K_{2010}.

Table 7. The exposure indices EI_J and EI_E with respect to the basic restrictions in ICNIRP 1998 and 2010 guidelines at d = 10 cm.

Heating power level	Exposure index [%]					
	EI_J (ICNIRP 1998 guidelines)			EI_E (ICNIRP 2010 guidelines)		
	Spheroid	IEC 62311	Anatomical	Spheroid	IEC 62311	Anatomical
1	8.9430	9.6696	4.1102	0.3817	0.4127	0.2321
2	12.8614	13.9049	5.9104	0.5490	0.5935	0.3337
3	14.6001	15.7846	6.7094	0.6232	0.6737	0.3788
4	18.8244	20.3517	8.6507	0.8035	0.8687	0.4884
5	23.1051	24.9796	10.6179	0.9862	1.0662	0.5995
6	24.6827	26.6852	11.3429	1.0536	1.1391	0.6404
7	24.8611	26.8781	11.4249	1.0612	1.1473	0.6450
8	27.5462	29.7811	12.6588	1.1758	1.2712	0.7147

field in the human body that can be compared with the basic restriction exposure limits. Thus, the exposure indices calculated in this chapter (EI_J and EI_E) are practical values that can alleviate the overestimation issue associated with the magnetic field exposure index EI_B.

4. Conclusion

In this paper, the human exposure to magnetic field from a commercial household induction cooktop was assessed using two methods. In the first method, the magnetic field distribution from the induction cooktop was measured, and the exposure indices were calculated with respect to the reference levels in the EMF guidelines. The exposure indices with respect to the reference levels in ICNIRP 1998 guidelines were lower than 83.73 % for all cases considered, and those with respect to the reference levels in ICNIRP 2010 guidelines were lower than 19.38 % for all cases considered.

In the second method, for the first time, the assessment method using the equivalent coil and the coupling factor is used for an induction cooktop. Coupling factors were calculated using various human models and equivalent sources. Equivalent sources were obtained using the measured magnetic field distribution from the induction cooktop. Using the coupling factor, the induced current density and electric field in the human body were estimated, and the exposure indices with respect to the basic restrictions were calculated. The estimated exposure indices with respect to the basic restrictions in ICNIRP 1998 guidelines were lower than 29.78 % for all cases considered, and those with respect to the basic restrictions in ICNIRP 2010 guidelines were lower than 1.27 % for all cases considered. It is expected that the assessment method using the coupling factor can provide an acceptable and practical alternative for the non-uniform magnetic field sources such as induction cooktops while avoiding the overestimation issues associated with the reference levels.

References

[1] B. Kos, B. Valič, D. Miklavčič, T. Kotnik, and P. Gajšek, Phys. Med. Biol. **56**, 6149 (2011).
[2] International Commission on Non-Ionizing Radiation Protection, Health Physics **74**, 494 (1998).
[3] International Commission on Non-Ionizing Radiation Protection, Health Physics **99**, 818 (2010).
[4] IEEE Standard C95.1-2005, IEEE, New York (2006) pp 14-15.
[5] International Standard IEC 62311, IEC, Geneva (2007).
[6] 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**, N23 (2010).
[7] M.-C. Gosselin, E. Neufeld, H. Moser, E. Huber, S. Farcito, L. Gerber, M. Jedensjö, I. Hilber, F. Di Gennaro, B. Lloyd, E. Cherubini, D. Szczerba, W. Kainz, and N. Kuster, Phys. Med. Biol. **59**, 5287 (2014).
[8] http://www.itis.ethz.ch
[9] T. Sunohara, A. Hirata, I. Laakso, V. De Santis, and T. Onishi, Phys. Med. Biol. **60**, 8129 (2015).
[10] J.-H. Shim, M.-S. Choi, K.-J. Jung, J.-H. Kwon, and J.-K. Byun, J. Magn. **21**, 516 (2016).
[11] K.-J. Jung, J.-H. Shim, M.-S. Choi, and J.-K. Byun, IEEE Trans. Magn. **54**, 5000104 (2018).
[12] Sim4Life by ZMT (www.zurichmedtech.com).