SAR Assessment of a Human Body Exposed to Electromagnetic Fields from a Wireless Power Transfer System in 10 MHz Band

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Abstract

Wireless power transfer (WPT) technology has attracted great attention for its high transfer efficiency with a long transfer range. Concerning biological hazards caused by strong electromagnetic fields in proximity to the WPT system, the dosimetry of the WPT system needs to be investigated in detail. In this paper, exposure assessment of the WPT system with a homogeneous cylinder in various operating situations possible was performed to characterize the dosimetry. It was found that the maximum allowable input power of the WPT system is restricted based on the whole-body average specific absorption rate (SAR) rather than the peak 10g-average SAR for some exposure conditions. Finally, a hybrid MoM/FDTD method is used to calculate the induced electric field inside the realistic human body and maximum allowable power into the WPT system.

1. Introduction

A wireless power transfer (WPT) system using magnetically coupled coils has been first experimentally demonstrated by Kurs *et al* [1] in 2007. There have been many studies on promising applications of the WPT system such as wireless feeding of electric appliances and charging electrical vehicles since then. In view of the human safety of radio waves, since much higher power than one used in wireless communication is applied in the WPT systems, exposure assessment of such systems needs to be investigated. In particular, the maximum allowable input power which secures human exposure limits prescribed in the international safety guidelines [2][3] is of concern.

Christ *et al.* [4] performed numerical dosimetry of a WPT system using a single loop coil at 8 MHz by the finite-difference time-domain (FDTD) method with assumption that backscattering from a human body is negligible. Park *et al.* [5] conducted dosimetry of a WPT system at 10 MHz with a two-step method using the impedance method and the method of moments (MoM) and compared the results with those calculated by the two-step approach combining the MoM and the FDTD method. A similar two-step approach has been done by Laakso *et al.* with use of the MoM and the scalar-potential finite difference (SPFD) method for the WPT system in both MHz- and kHz-band frequencies [6][7]. The use of two-step approaches with quasi-static approximation assumes that the human body does not disturb the current distribution of the coils and the effect of electric near-fields is negligible. However, the effect of the electric fields may not be considered marginal in some exposure condition. In addition, although the validity of the quasi-static approximation has been confirmed in some exposure condition by using the peak 10g-averaged specific absorption rate (SAR_{10g}) as a metric in [8], the validation for the whole-body average SAR (SAR_{wb}) was not shown in the reference.

This paper pays much attention on the SAR_{wb} caused by an exposure of electromagnetic fields nearby the WPT system since it may represent the worst-case scenario of exposure in some case. First, we briefly describe the WPT system used in this study. Then, we performed exposure assessment of the WPT system with a homogeneous dielectric cylinder in many operating situations possible. Finally, we calculate the induced electric field inside the realistic human body and maximum allowable power into the WPT system by using a hybrid MoM/FDTD method [9][10], which can take into account mutual interaction between the resonant coils and the human body.

2. Wireless Power Transfer System

Figure 1 illustrates the geometry of a wireless power transfer system, consisting of two resonant coils with primary loops for feeding and receiving power. Radii of the one-turn loops and the resonant coils with 6.1 turns are 25 cm and 30 cm, respectively. The coils and loops were modelled as perfect conductor with a diameter of 1.6 mm. Internal and load resistances at the feeding and load ports are both 50 Ω. The electromagnetic full-wave analysis was carried out with the MoM using the commercial software 'FEKO'. Separation distance between the resonant coils is fixed at 20 cm for all analyses in this study. Power transfer efficiencies of 99.5% and 99.9% were measured at two resonance frequencies of 9.17 MHz (f_{low}) and 10.25 MHz (f_{high}), respectively.

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3. Dosimetry of Cylindrical Human Model Close to WPT System

A simple homogeneous cylindrical human model is considered here. The height, diameter, and weight of the cylinder are 1.7 m, 0.14 m, and 104 kg, respectively, which is the same as those used in [8]. Dimensions of the cylinder are chosen so as to correspond to the size of an adult human. The dielectric constant is chosen as two-third of that of muscle; i.e., a relative permittivity of 120.9 and conductivity of 0.41 S/m. Three specific scenarios of exposure are considered as shown in Fig. 2. The nearest distance d from the resonant coils to the surface of the cylinder is 10, 60, and 150 mm. The input impedance of the feeding port is adjusted by loading a capacitor to maximize the transfer efficiency without changing the frequency in all full-wave analyses in this section.

Table 1 shows the results at 9.17 MHz (f_{low}) obtained by the MoM. Both SAR_{wb} and SAR_{10g} are determined for an input power of 1 W. The maximum allowable input powers (P^{in}_{max}), which satisfied human exposure limits in the guidelines [2] for the SAR_{wb} (0.08 W/kg) and SAR_{10g} (2 W/kg) are also shown in the Table 1. For the case (A), the P^{in}_{max} is restricted based on the SAR_{10g} when d = 10 mm. However, the SAR_{10g} decreases rapidly with respect to the increase of the distance d and, in consequence, the SAR_{wb} is a main cause to limit the P^{in}_{max} for a longer distance. For the case (B), the P^{in}_{max} is restricted based on the SAR_{wb} even when the distance between the WPT system and the cylinder is as close as d = 10 mm. For the case (C), the situation is similar to the case (A), where the SAR_{10g} decreases rapidly when d increases. The P^{in}_{max} restricted based on the SAR_{10g} is almost identical to that of the SAR_{wb} when d = 60 mm. From Table 1, it was found that the most restricted condition for the input power is the case (C) with d = 10 mm, where P^{in}_{max} = 61 W.

Table 2 shows the results at 10.25 MHz (f_{high}) obtained by the MoM. The P^{in}_{max} for the SAR_{wb} and SAR_{10g} have the same tendency with those at f_{low} in all cases considered here. The most restricted condition for the input power is the case (A) with d = 10 mm, where P^{in}_{max} is only 19 W. The transfer efficiency for this case is reduced to nearly 17%, which is not practical for the real system. Therefore, depending on the exposure condition, the SAR_{wb} may be more restrictive than the SAR_{10g} as in the case (B). However, the analyses in this section were performed by using only the homogeneous cylindrical human model, while the results using a realistic human model may differ distinctly with the above results, especially for the SAR_{10g} which depends largely on the inhomogeneity and shape of the human model.

4. Dosimetry of Human Model Close to WPT System Using MoM/FDTD Method

In order to evaluate the SAR in a realistic human model, we apply a hybrid MoM/FDTD method to the dosimetry of the WPT system. The MoM/FDTD method can take into account the mutual interaction between the resonant coils and the human body by iterative calculations of backscattered electromagnetic fields. The validity of our hybrid MoM/FDTD code has been confirmed in [10]. Here, an MRI-based Japanese adult human model TARO was considered [11]. The model has a resolution of 2 mm and consists of 58 tissues. Exposure condition is shown in Fig. 3, which is the same situation as that for the case (A) in Fig. 2. The closest distance from the resonant coils and the human body is 120 mm and an averaged distance from the coils to the surface of the human back is approximately 150 mm.

By using the MoM/FDTD method, the input impedance converged in 2 iterations and was determined as 51.7 + j13.4 Ω, whereas the transfer efficiency decreases from 99.4% to 94.4%. The SAR_{wb} and SAR_{10g} for an input power of 1 W were 0.192 mW/kg and 1.625 mW/kg, respectively, as a result of the first iteration of calculation and decrease to 0.191 mW/kg and 1.596 mW/kg, respectively, in the second iteration. These values corresponds to the P^{in}_{max} of 416 W and 1230 W, respectively. It was observed that the P^{in}_{max} for the SAR_{wb} is more restrictive than that for the SAR_{10g} as described in Section 3 for this case. Comparing with the results for the case (A) of d = 150 mm at f_{low}, since the cylinder used in the section 3 is heavier than the human model (70 kg), the SAR_{wb} of the human model is somewhat higher than that of the cylinder as expected while the SAR_{10g} of the human model is almost three time larger than that of the cylinder. This may be attributed to the inhomogeneity of the model. Figure 4 illustrates the induced electric field distribution inside the human body calculated by using the MoM/FDTD for an input power of 1 W.

5. Conclusion

Exposure assessment of a human body exposed to electromagnetic near-fields from a wireless power transfer system has been performed. It has been shown that the SAR_{wb} limits the maximum allowable power for the case where the human body is placed at the back of the WPT system. We have performed a numerical dosimetry of a realistic human model by using the MoM/FDTD method and determined the SAR and the maximum allowable input power compared to those of the cylindrical model. It has been shown that the SAR_{wb} is more restrictive in the situation such as the case (B).

* Analysis results using the realistic human model for the other cases will be reported in the conference.

6. References

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Table 1. Dosimetry results of dielectric cylinder in vicinity of the WPT system at f = 9.17 MHz (f_{low})

Case	Distance d (mm)	SAR_{wb} (mW/kg)	SAR_{10g} (mW/kg)	Maximum allowable input power P^{in}_{max} (W)		Transfer efficiency (%)
				SAR_{wb}	SAR_{10g}	
(A)	10	0.470	17.71	170	113	71.6
	60	0.276	2.07	290	966	92.4
	150	0.133	0.57	560	3508	97.6
(B)	10	0.735	6.97	109	287	89.2
	60	0.486	4.79	165	418	93.6
	150	0.241	2.16	331	927	96.8
(C)	10	0.326	32.60	246	61	91.7
	60	0.148	3.76	533	531	97.7
	150	0.062	0.82	1288	2452	98.8

Table 2. Dosimetry results of dielectric cylinder in vicinity of the WPT system at f = 10.25 MHz (f_{high})

Case	Distance d (mm)	SAR_{wb} (mW/kg)	SAR_{10g} (mW/kg)	Maximum allowable input power P^{in}_{max} (W)		Transfer efficiency (%)
				SAR_{wb}	SAR_{10g}	
(A)	10	1.950	107	41	19	17.0
	60	0.571	8.56	140	234	74.2
	150	0.153	1.70	524	1178	96.8
(B)	10	0.688	7.10	116	282	82.1
	60	0.420	4.59	190	436	93.8
	150	0.180	1.92	444	1040	97.8
(C)	10	0.927	60.8	86	33	51.9
	60	0.365	11.0	219	181	97.8
	150	0.111	2.15	720	929	98.5

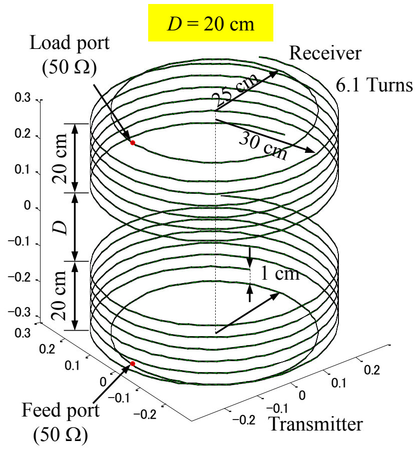

Fig. 1. Geometry of the WPT system including two resonant coils and two loops.

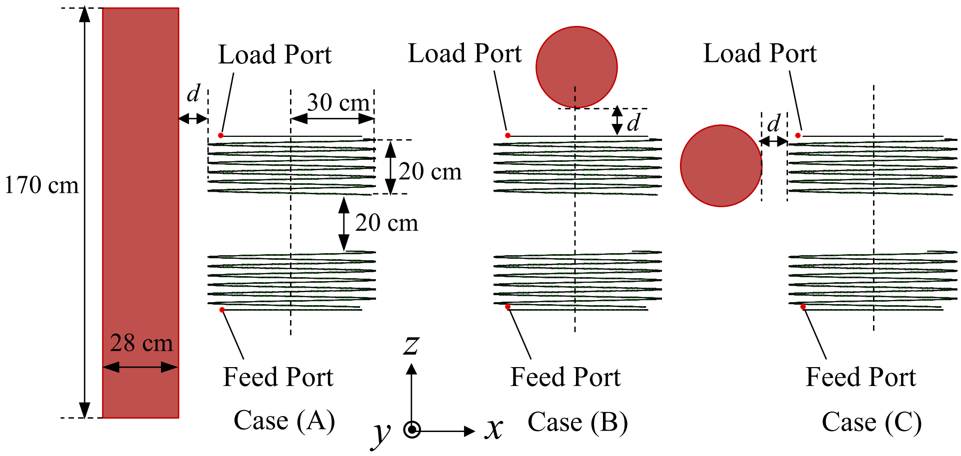

Fig. 2. Exposure conditions and positions of dielectric cylinder relative to the resonant coils.

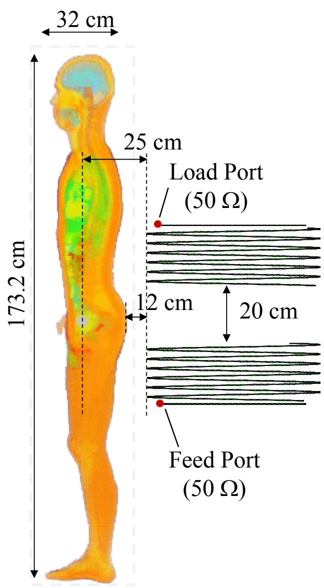

Fig. 3. Exposure condition and position of the human body relative to the resonant coils.

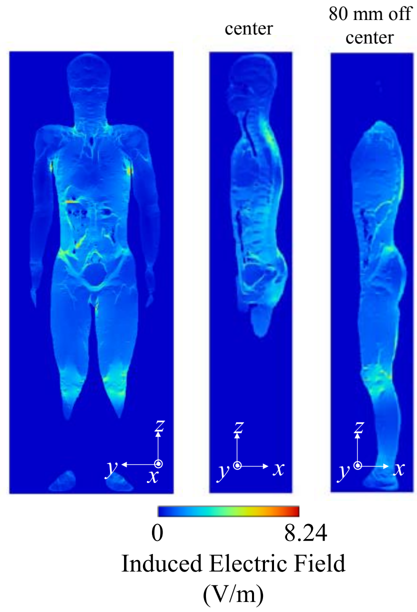

Fig. 4. Induced E-field distribution inside the human body calculated by the MoM/FDTD method.