Induced Field and SAR in Human Body Model Due to Wireless Power Transfer System with Induction Coupling

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Abstract— **The present study investigates the SAR (specific absorption rate) and the induced electric field in an anatomically based model for the magnetic field from a wireless power transfer system. The waiting and charging conditions are considered. The transfer frequency considered herein is from 100 kHz and 150 kHz where a magneto-quasi-static approximation is valid. A two-step quasi-static method comprised of the method of moments and the scalar potential finite difference method is then used. First, the method of moments is used to calculate the magnetic field of wireless transfer system without the presence of the human body model. Then, the SAR and the electric field in the model are calculated by solving the scalar potential finite difference method. From computational results, the peak values of the SAR averaged over 10 g of tissue and the induced electric field for the transfer power of 5 W are substantially smaller than 2 W/kg and 18.9 V/m, the basic restrictions for those for general public, prescribed in the international guidelines/standard. The results indicate the induced electric field as a dominant factor when evaluating the compliance of the wireless power transfer system.**

Keywords— quasi-static approximation; scalar potential finite difference method; specific absorption rate (SAR) ; induced electric field ; wireless power transmission

I. INTRODUCTION

There has been increasing concern for realizing a wireless power transfer system [1]. Attention is needed on the human safety of radio waves used in such systems since the expected transmitting power is much larger than that used in wireless communications. In particular, the maximum allowable transmitting power that satisfies human exposure limits prescribed in international safety guidelines/standards [2, 3] is of interest to design the system. The frequency bands considered for wireless power transfer with magnetic induction is the range of a hundred kilohertz or higher. One of the possible applications is to charge mobile phones which has been introduced and become popular in Japan [4]. Users can charge their mobile phones not only at their home but also at some public areas and shops. Although the current available transmitting power is 5 W, it is being planned to extend to 50

W or higher, in order to apply to tablets, laptop PCs, and so on. The external field strength from such systems may exceed the reference level or the limit in the international guidelines [3]. In that case, the compliance with basic restrictions, i.e., local SAR and induced electric field, should be evaluated [2, 3]. Note that both the specific absorption rate (SAR) and the in-situ electric field induced are used as metric for human protection at frequencies from 100 kHz to 10 MHz.

In the present study, a two-step quasi-static method comprised of the method of moments (MoM) and the scalar potential finite difference (SPFD) method [5] is used to investigate the induced field and the SAR in anatomically based human models. Our computational modeling of the wireless power transfer system is confirmed by comparing with computed and measured magnetic field distributions.

II. MODEL AND METHOD

A. Modelling of Coils

Figure 1 (a) illustrates the geometry of two coils consisting a wireless power transfer system with induction coupling. In commercial software named FEKO, the coils were modeled as perfectly conducting thin wires with a diameter of 0.5 mm, and the system was excited by a voltage source located at port 1. The inner and outer diameters of the coils are Di=12 mm and Do=40 mm, respectively, and the number of turns is 20. The separation between two coils Dz is 3.5 mm. The coils are covered by the square-shaped magnetic sheets. The dimension of the magnetic sheet is 55 mm × 55 mm × 0.6 mm and its relative permeability is 7000. The distance between the coil and magnetic sheet is 0.5 mm. A matching load is connected to receiving and transmitting coils to realize high transfer efficiency. The transmitting power is normalized as 1 W. In addition to the 'charging' condition, i.e., the transmitting coil with the magnetic sheet only is considered to simulate the 'waiting' condition.
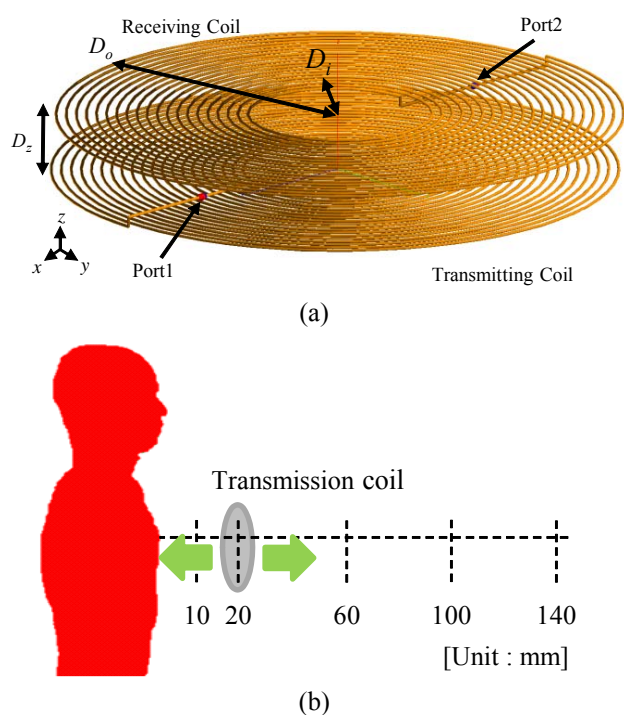
B. Computational Method

(a)

(b)

Fig. 1. The configuration of the transmitting and receiving coils with the human body model; (a) the details of transmitting and receiving coils and (b) the relative position of the human body model to the coils.

The displacement current is negligible when compared with the conduction current because the magneto-quasi-static approximation is applicable in the frequency band of kHz. The magnetic field generated by the induction coils is first obtained using the MoM without considering the human model. The induced electric field is then computed by solving the SPFD equation system numerically. The SPFD equation system was solved by a multi-grid method [6]. The simplification for using the external field without the human body is supported by the fact that i) the human body behaves as a conductor and thus ii) the SAR is primarily caused by the external magnetic field rather than the electric field. Note that this simplification is validated even in the 10 MHz band for wireless power transfer with magnetic resonance [5].

The SAR evaluation is essential for the charging condition as the SAR should be averaged over 6 min. [2, 3] while the time averaging procedures are not needed for compliance of *induced* electric field. The electromagnetic field emitted in the waiting condition is a pulse signal and thus the time averaging value of the SAR would be smaller than that presented below, which is assumed to be continuous wave. However, both metrics are evaluated in this study as the regulation may not be well defined at this moment for the waiting condition.

C. Exposure Scenario with Anatomically Based Human Body Model

This study employed the Japanese male model TARO [7] comprising 51 anatomical tissues/organs such as skin, muscle,

bone, brain, heart and so on. The resolution of the model is 2 mm. The human body is located in front of the coil, with the height of the coil in front of the chest, as shown in Fig. 1(b). The distance between the model and the transmitting coil is changed from 10 mm to 140 mm. Note that only the upper half of the human model is used because local exposure of the chest is considered in the scenario; the coils are much smaller than the human body dimension.

Compared to a full-wave analysis (e.g. the finite difference time domain method), the source magnetic field needs to be solved only once for a single system configuration. This leads to a greatly reduced computational effort, especially when studying a variety of different human body models/human-coil positions.

D. Experimental Procedure for Validation

Transmitting and receiving coils conformed to the specifications by Wireless Power Consortium (WPC) [8] are used to measure magnetic field distributions around the coils. The magnetic probe 11941A (Agilent technology, USA), whose frequency range is from 9 kHz to 30 MHz, is employed. Firstly frequency components of waiting and charging modes are measured to confirm a fundamental frequency, respectively. Then magnetic field distributions at the frequency are measured with the interval of 10 mm on xy and yz planes, respectively.
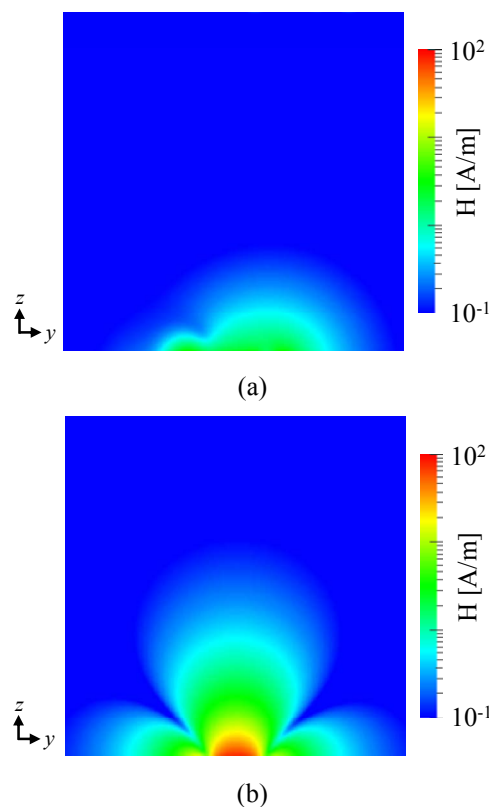

(a)

(b)

Fig 2. Computed magnetic field distribution for (a) charging and (b) waiting conditions.
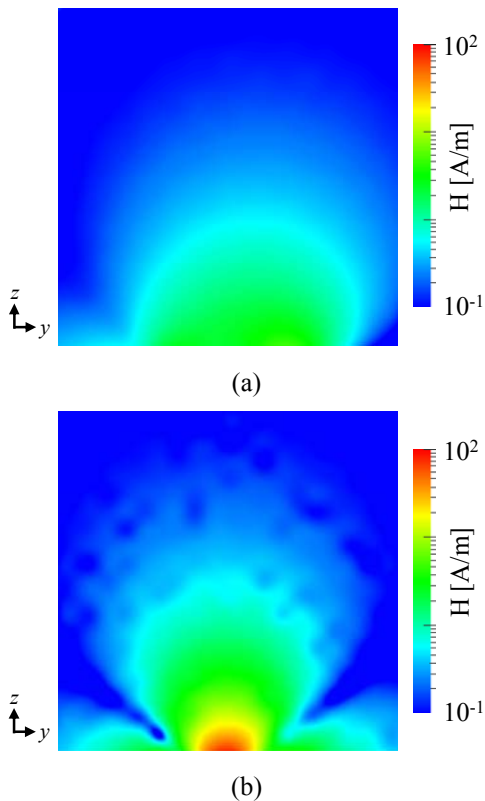
Fig. 3. Measured magnetic field distribution for (a) charging and (b) waiting conditions.

III. CONFIRMATION OF COMPUTATIONAL MODELING

In order to confirm the field distribution generated by the transfer system, the measured and computed results are compared for charging and waiting conditions. Thus, the computed and measured magnetic fields are normalized by the maximum amplitude. The frequency of 140 kHz was chosen in the following comparison.

The computed and measured magnetic field distributions in the waiting and charging conditions are shown in Figs. 2 and 3, respectively. From these figures, good agreement is observed between the measured and computed results for the waiting condition, whereas fair agreement for the charging condition. One of the possible reasons for this difference is attributable to the internal circuit of the receiver, which is not well modeled in the computational simulation.

It should be noted that the magnetic field distribution without the magnetic sheet is symmetry. Thus, the disturbance of the field is primarily attributable to the insertion of the magnetic sheet. In addition, the magnetic field intensity becomes somewhat stronger around the feeding points of the coils. Comparing Figs. 2 and 3, the magnitude of magnetic field in the charging condition is smaller than that in the waiting condition, because the most transmitting power is received at the receiving coil.

For the magnetic field distributions shown in Figs. 2, the SAR and the induced electric field in the human model were calculated by the SPFD method for different separations. Note that the magnitude of the magnetic fields is normalized as 1 W.
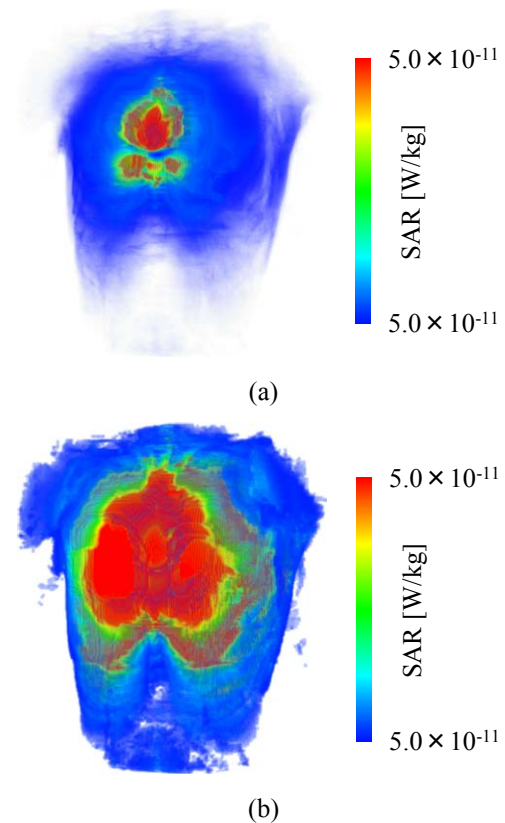

Fig. 4. The SAR distribution in the model ($D = 10$ mm) for (a) charging and (b) waiting conditions.
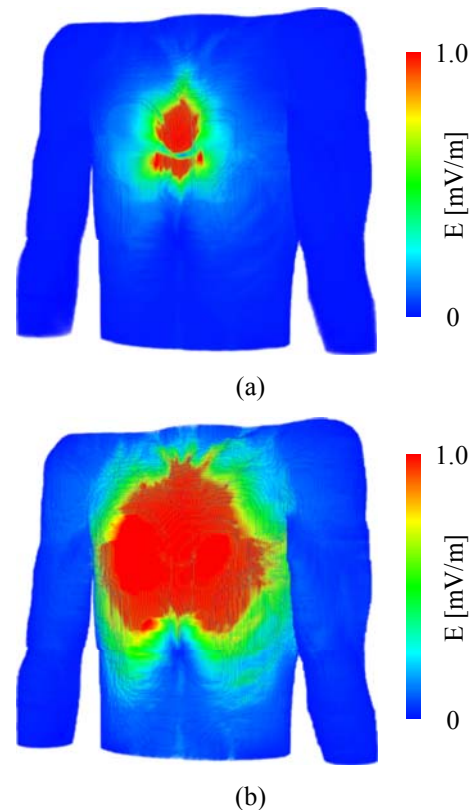

Fig. 5. The E distribution in the model ($D = 10$ mm) for (a) charging and (b) waiting conditions.
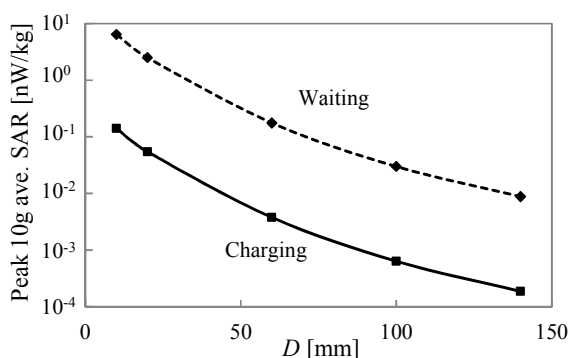
Fig. 6. The dependence of peak 10 g averaged SAR on the coil-body separation.
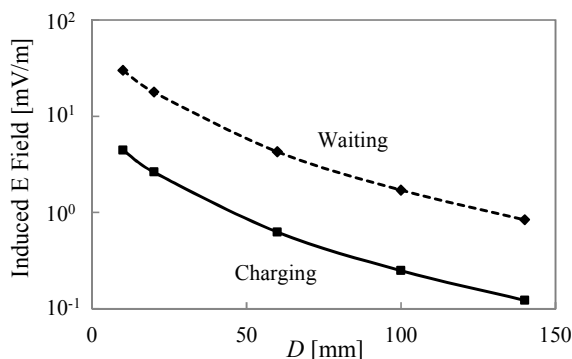

Fig. 7. The dependence of induced electric field on the coil-body separation.

The SAR distribution in the human model is shown in Figs. 4 (a) and (b) for the charging and waiting conditions, respectively. Comparing Figs 4 (a) and (b), most of the SAR distributions are located in the chest, which is the closest body part to the coil. Furthermore, the SAR value for the waiting condition is larger, as expected. Likewise, Figs. 5 (a) and (b) show the induced electric field distribution in the human model for the charging and waiting conditions, respectively. As shown in the figures, the induced electric field distributions are similar to the SAR distributions in Fig. 4. Figure 6 shows the dependence of peak 10 g averaged SAR on the body-transmitting coil distance. As shown in Fig. 6, the peak averaged SAR in the waiting condition is higher than that in the charging condition, as is the same as the distribution in Fig. 4. The peak SARs for charging and waiting conditions at $D = 10$ mm are 0.14 nW/kg and 6.4 nW/kg, respectively, and decrease exponentially for both the conditions. The allowable transmitting power in this system to satisfy the SAR limit of 2 W/kg [2] is 300 MW.

In the calculation, the maximum strength of the magnetic field which the model was exposed to was 13.0 A/m. This limits the transfer power to 0.38 W since it exceeds the reference level of 5 A/m [2]. However, the peak value of the SAR and the induced electric field were under the basic restrictions, allowing the system to transfer larger power. In addition, the average strength of the magnetic field exposed to the model was 51 mA/m, and is predicted to be significantly smaller when a whole-body model is employed.

The maximum magnitude of the induced electric field are, as shown in Fig. 7, 4.5 mV/m and 30.0 mV/m for the charging and waiting conditions at $D = 10$ mm, respectively. Similar to the SAR characteristics in Fig. 6, the induced electric field in the waiting condition is higher than that in the charging condition. The basic restriction for the induced electric field at 140 kHz is 18.9 V/m [2]. Thus, the allowable transmitting power to satisfy the electric field limit is 630 W. Note that the maximum electric field was induced in fat in all the cases. From the results above, it is obvious that the allowable transmitting power is lower when considering the induced electric field than the SAR.

IV. SUMMARY

This study investigated the SAR and the induced electric field in an anatomically based human body model due to the magnetic field from a wireless power transfer system. The transfer system was comprised of two induction coils covered by the magnetic sheets. The transfer frequency considered herein is 100 kHz band. The waiting and charging conditions were considered. From computational results, the peak value of SAR averaged over 10 g of tissue is 6.4 nW/kg for the transfer power of 1 W, which is much smaller than that of the basic restriction of 2 W/kg prescribed in the international guidelines/standard. On the other hand, the maximum magnitude of the induced electric field is 30.0 mV/m. Compared to the SAR, the ratio of the induced electric field to the basic restriction of 18.9 V/m is not as small as that of the SAR. Thus, the allowable transmitting power in this system to satisfy the induced electric field limit of 18.9 V/m is 630 W. The computational result obtained herein confirms that the compliance of basic restriction for the induced electric field is essential rather than peak 10 g averaged SAR.

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