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Misaligned Effect and Exposure Assessment for Wireless Power Transfer System Using the Anatomical Whole-Body Human Model

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Abstract—This paper presents dosimetry of a high resonance wireless power transfer (HR-WPT) system when the transmitter and receiver are aligned and misaligned. An HR-WPT system with two resonant coils and two feeding loops, operating at 13.56 MHz is designed. The power transfer efficiency of the system, and the electric and magnetic fields are investigated using the method of moments. The power transfer efficiency in misalignment situations can be increased by matching the HR-WPT system. Dosimetry of the HR-WPT system is conducted at the optimum matching condition for alignment and misalignment, to achieve the best power transfer efficiency. The specific absorption rate (SAR) is computed using a two-step approach. In the first step, the magnetic fields generated by the HR-WPT system in the absence of a whole-body voxel human model are calculated using the method of moments. In the second step, the SAR in the human model is calculated using the impedance method, with the magnetic fields computed in the previous step regarded as the magnetic fields incident to the human body. Five exposure scenarios are set: one alignment condition and four misalignment conditions. The SAR computed for the alignment and misalignment cases in the matching condition are compared to each other. The compliance of the system is also investigated using the international safety guidelines. Finally, the maximum allowable powers to comply with the guideline are investigated for the five cases considered. The results show that the SARs observed in the misalignment case are higher than those in the alignment case. These results suggest that the misalignment situation should be considered in addition to alignment, when conducting dosimetry of the HR-WPT system.

1. INTRODUCTION

Since a research team at the Massachusetts Institute of Technology (MIT) proposed the creation of the wireless power transfer (WPT) technique using the magnetically coupled high resonance (HR) phenomenon [1], the technique has gradually been receiving greater attention. The WPT technique is expected to be useful for various applications such as cellular phones, laptop computers, home electrical appliances, and electric vehicles [2–6]. The convenience of power transfer in this manner is analogous to the difference between wireless and wired communication. However, the electromagnetic radiation produced by WPT applications is much stronger than with wireless communications. Therefore, it is necessary to investigate electromagnetic compatibility (EMC) and safe limits for human exposure to electromagnetic radiation, particularly with electric vehicle (EV) applications, where high powers, which produce very strong electric and magnetic fields, are required [7–10].

This work considers the possibility that the strong electric and magnetic fields generated by HR-WPT systems cause adverse health effects to the human body. Thus, the maximum allowable dose of electromagnetic radiation produced by the HR-WPT system for a human body should be estimated. The operating frequencies of applications that use HR-WPT systems are expected to range from several

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kilohertz to several megahertz. In this band, which is part of the intermediate frequency region defined by the World Health Organization (WHO) [11] as the region between 300 Hz and 10 MHz, the stimulation effect, which is dominant at lower frequencies, and the thermal effect, which is dominant at higher frequencies, must both be considered. The International Commission on Non-Ionizing Radiation Protection (ICNIRP) guidelines recommend protection against stimulation effects for frequencies up to 10 MHz and protection against thermal effects for frequencies between 100 kHz and 10 GHz [12, 13]. The value of the 99th percentile of the internal electric field, which is used in ICNIRP guidelines, is the metric used to provide the human exposure limit, for protection against stimulation effects. The specific absorption rate (SAR) is used as the metric for the human exposure limit, for protection against thermal effects. The compliance of the HR-WPT system with international electromagnetic field (EMF) safety guidelines should be investigated using these parameters. Dosimetry of the WPT system has been studied in [14–17]. Article [17] has briefly reported that electromagnetic field in the misalignment situation between the transmitting coil and receiving coil cause differences of that in the alignment situation as this case often arises in general operation of the system, and has conducted the dosimetry for only one misalignment exposure scenario.

In this study, a matching method to maintain maximum power transfer efficiency in the misalignment is discussed in detail, and dosimetry for the HR-WPT system is conducted for all misaligned exposure scenarios under matching condition to maintain maximum power transfer efficiency. In the misalignment situation, a matching system is activated so that the system operates with the best power transfer efficiency [3]. In this paper a comparison of the results of dosimetry, for the alignment and misalignment conditions, is presented. First, a HR-WPT system with four coils, for operation at 13.56 MHz, is designed. The features of the HR-WPT system along with the alignment and misalignment situation are investigated. For these situations, the electric and magnetic fields close to the system are calculated and compared to a reference, dictated by the ICNIRP guidelines. Finally, using the SAR, the electromagnetic radiation absorbed in the human body is also calculated for the two situations considered. The whole-body voxel human model is used to estimate the location and magnitude of the electromagnetic energy absorbed in the body precisely.

2. MATERIALS AND METHODS

2.1. HR-WPT System

The HR-WPT system is designed here as shown in Figure 1(a). High resonance is defined by the quality factor of the transmitting and receiving coils. The patent application made by the MIT research group that initially proposed this method dictates that the minimum quality factor required for high resonance is 500. The inductance and resistance of the transmitting and receiving coils used in this study at an operating frequency of 13.56 MHz, are 27.552 μH and 3.45 Ω, respectively. Thus, the quality factor of the system is approximately 680. The WPT system consists of two outer coils and two inner loops. The outer coils, which have 5 turns and a pitch of 5 mm are resonators that operate at 13.56 MHz when a 5 pF capacitance is added. Electromagnetic radiation is efficiently transferred through these outer resonant coils. The inner loops are used as a matching circuit. There are six coupling coefficients due to the mutual inductances between the two coils and the two loops. The three main coupling coefficients are the k1t coupling coefficient between the source loop and the transmitting coil, the ktr coupling coefficient between the transmitting coil and receiving coil, and the k2r coupling coefficient between the receiving coil and load loop. Along with the quality factor of the coil, the ktr coefficient is the main factor that affects power transfer efficiency [1] k1t and the k2r are related to input (port 1) and output (port 2) matching, respectively. k1t or k2r can be adjusted by increasing or decreasing the distance between the coil and the loop or the size of the loop. The outer coil radius of the HR-WPT system and the power transfer distance are set to 150 mm. Copper wire with a radius of 2 mm is used for the system. Misalignment between the transmitter and receiver is investigated, as shown in Figure 1(b), because this is often the situation during charging. Without matching, the power transfer efficiency in the misalignment case generally decreases. However, a practical WPT system is matched for power transfer efficiency. In this work, the power transfer efficiency is investigated with various misaligned distances (t) in matching and mismatching conditions. The HR-WPT system is simulated using a commercial electromagnetic solver (FEKO) based on the method of moments, to obtain the

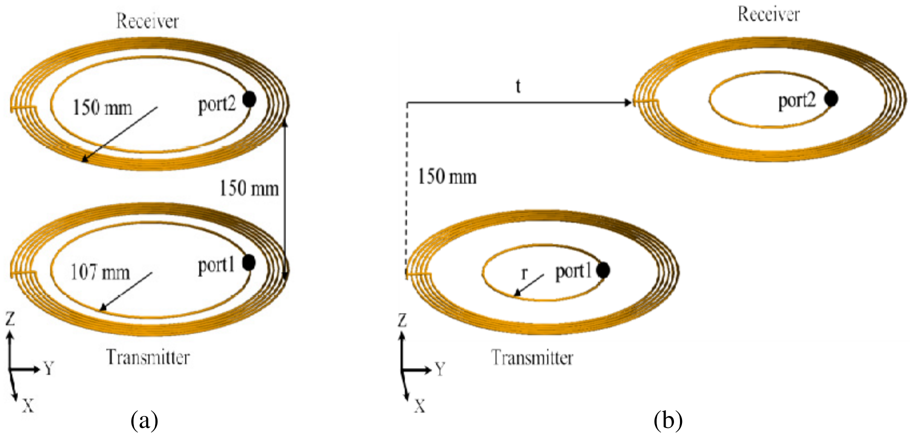


Figure 1. Configuration of high resonant wireless power transfer (HR-WPT) system for (a) alignment and (b) misalignment conditions.

power transfer efficiency and the electric and magnetic field close to the system [18] Both ports (port 1 and port 2) are terminated with a 50 Ω impedance. The wire is set by copper, which has a conductivity of 5.81×10^7 S/m. The transmitting and receiving coils are closed and a capacitance of 5 pF is added to the coils. The wire segment length for meshing is 20 mm.

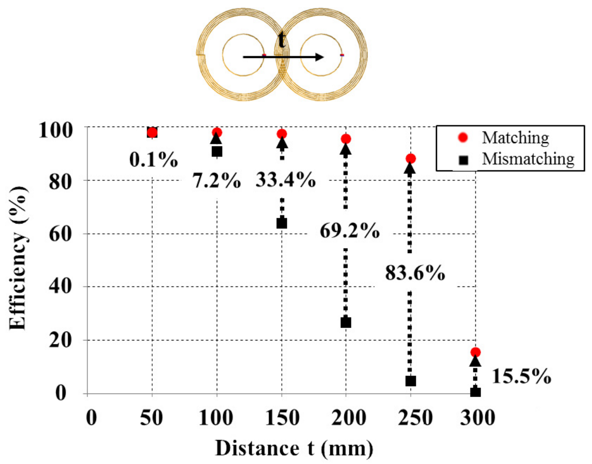
2.2. Whole-Body Voxel Human Model and Dosimetry

To determine if the EMF generated by the HR-WPT system used in the vicinity of a human body is safe, dosimetry of the system in aligned and misaligned conditions is conducted using TARO, an anatomically realistic Japanese adult male model [19]. This human model possesses 2 mm spatial resolution and 51 tissues and organs, based on images accumulated from magnetic resonant imaging (MRI) of adult Japanese volunteers. The electrical properties of the TARO model are taken from Gabriel's Cole-Cole models. The SAR in the human body is calculated using a two-step computation method. In the first step, the magnetic fields produced by the HR-WPT system are obtained in the absence of the human body using FEKO. In the second step, the SAR in the human body is calculated using the impedance method, by considering the fields obtained in the previous step as the incident fields [20]. It should be noted that this two-step computation method does not include interaction effects between the WPT system and the human body. However, because of the weak backscattering from the human body, the interaction effects can be ignored [15]. The magnitude of the interaction of effects was quantified in [14], when a cylindrical human phantom was placed 10 mm away from the coil of the wireless charging system. The maximum difference over the whole cylinder normalized by the maximum magnetic field was 4.8%, which can be ignored.

3. RESULTS AND DISCUSSION

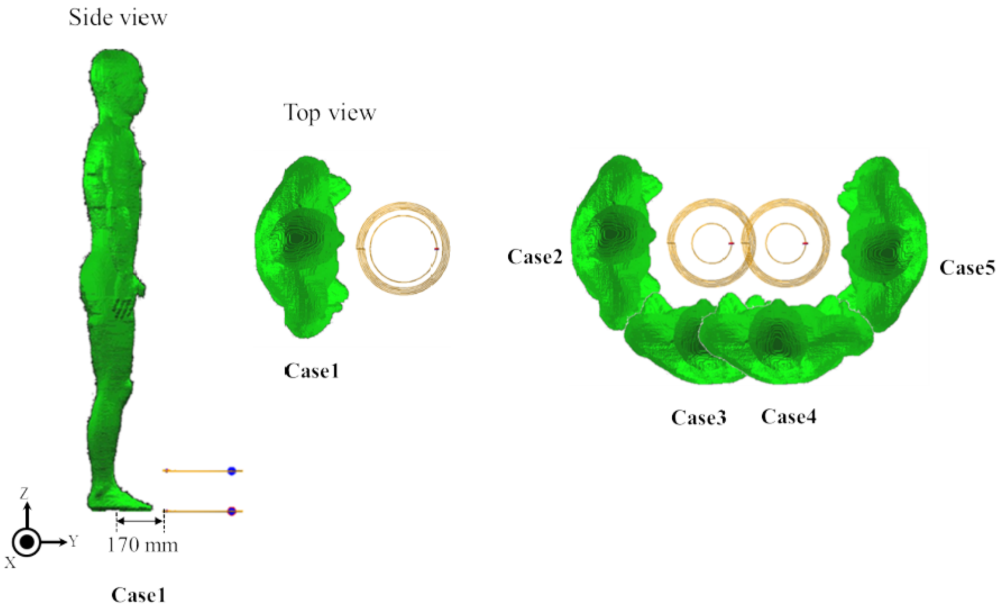
3.1. Features of HR-WPT System and EMF Reference Level

The computed power transfer efficiency of the HR-WPT system considered in this study is 98% in the alignment case. The power transfer efficiencies in the misalignment case, for the matching and mismatching conditions along with the misaligned distance (t) are shown in Figure 2. The matching condition is achieved by adjusting the radius, r, of the inner loop. As the misaligned distance t increases, the coupling coefficient, ktr, becomes smaller. k1r and k2t should also be reduced, in addition to ktr, for matching purposes. Therefore, because of the matching process, the overall tendency is that the radius of the loop decreases as the misaligned distance increases. In this study, the radius is gradually decreased from 107 mm when t is 0 mm to 37 mm when t is 300 mm. Detailed values are listed in Figure 2.



t (mm)	50	100	150	200	250	300
r (mm)	106	102	94	82	67	37

Figure 2. Comparison of computed power transfer efficiencies of the HR-WPT system in matching and mismatching conditions The table depicts the radius of the loop (r) for matching along the corresponding misaligned distance (t).

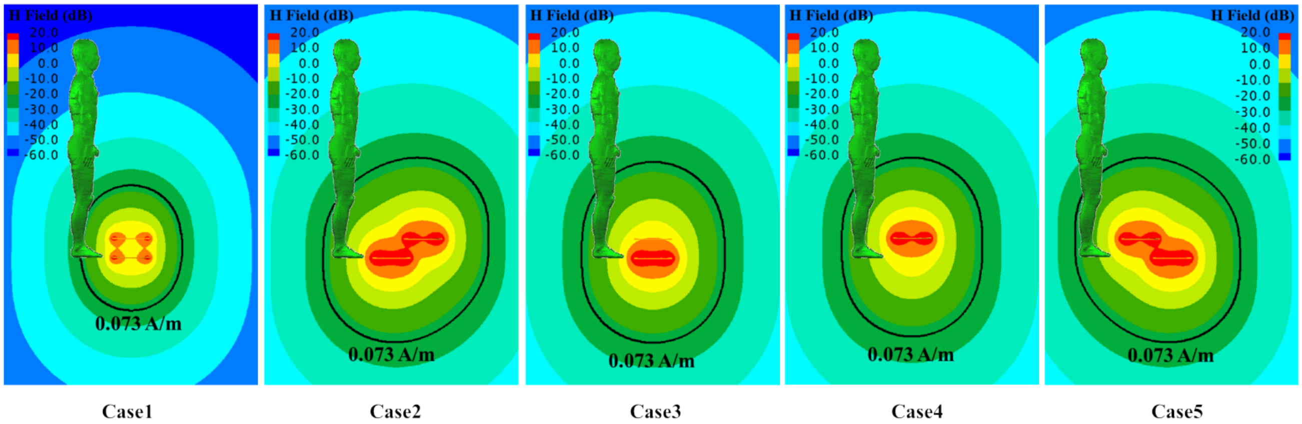


(a) (b)

Figure 3. Position of human body model with respect to HR-WPT system in (a) the alignment condition (Case 1) and (b) four misalignment conditions (Case 2–Case 5).

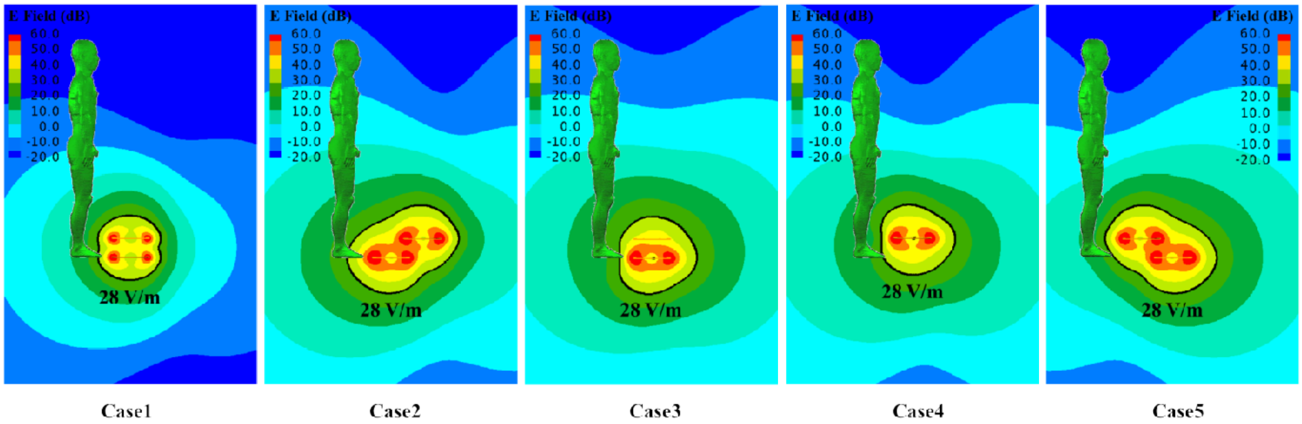
The input impedance is modified along with the coupling coefficient (k1t or k2r) between the inner loop and the outer coil. This coupling coefficient depends on the mutual magnetic flux between the outer coil and the inner loop. Thus, the matching condition can be found easily, by adjusting the size of the loop to modify the input impedance. Without matching, the power transfer efficiency drops rapidly as the misaligned distance increases. Thus, matching improves the power transfer efficiency. An efficiency improvement of 83.6%, which is the best value observed, is noted at a misaligned distance of 250 mm. At this distance, the difference in the magnitude of the radiation emitted by the HR-WPT system in the alignment and misalignment situations is the largest. Therefore, the maximum dose for the HR-WPT system is estimated in this misalignment condition ($t = 250\,\mathrm{mm}$). The results computed in misalignment are compared with those of the alignment condition. Five exposure scenarios (Cases 1 to 5) are estimated as shown in Figure 3. The human body model used for dosimetry in the five exposure scenarios has a volume of $640\,\mathrm{mm} \times 320\,\mathrm{mm} \times 1732\,\mathrm{mm}$ ($x \times y \times z$). The wireless charging coil is as described in Subsection 2.1. The sole of the human body and the transmitting coil are located at the $z = 0$ coordinate. The receiving coil is placed 150 mm away from the transmitting coil. In Case 1 and Case 2, the center of the human body is located 320 mm from the center of the transmitting coil in the y direction, and in Case 3, the center of the human body is located 320 mm from the center of the transmitting coil in the x direction. The body in Case 4 and Case 5 is located 320 mm from the center of the receiving coil in the x and y directions, respectively.

The reference electric field strength and magnetic field strength, dictated by the 1998 ICNIRP guidelines, are 28 V/m and 0.073 A/m, respectively, at 13.56 MHz. The electric and magnetic field strengths close to the HR-WPT system are calculated to investigate the reference level of the system. The magnetic and electric field strength distributions close to the system, when a 1 W input is used, are shown in Figures 4 and 5, respectively. In these images, the reference level is depicted as a solid black line. Although the field distributions are calculated in the absence of a human body, the results are



Case1 Case2 Case3 Case4 Case5

Figure 4. Magnetic field strength distribution close to the HR-WPT system for alignment and misalignment cases. The solid black line indicates the reference level defined by the ICNIRP guidelines.



Case1 Case2 Case3 Case4 Case5

Figure 5. Electric field strength distribution close to the HR-WPT system for alignment and misalignment cases. The solid black line indicates the reference level defined by the ICNIRP guidelines.

shown with a human body model to investigate the compliance with the ICNIRP guidelines. As shown in the results, the area where the reference levels are exceeded is wider for the magnetic field strength, than it is for the electric field strength. It can also be seen that the area where the reference levels are exceeded is wider in the misalignment condition than in the alignment condition. In the case of alignment, the horizontal distance and the vertical distance from the wireless charging coil to the black solid line, which represents the reference level, are 183 mm and 302 mm, respectively. The horizontal and vertical distances are 297 mm and 423 mm, respectively, in the misalignment cases.

3.2. Dosimetry with the Human Body Model and Basic Restriction

The SARs in the human body are calculated for the five exposure scenarios shown in Figure 3. The EMF problem is more serious in applications requiring high powers, such as electric vehicles rather than low power applications such as mobile phones. The exposure scenarios mentioned above, are thus set on the assumption that a person stands in front of a WPT system for electric vehicles located on the floor. The localized SAR (SAR_{10g}) and whole-body SAR (SARwb) for the five cases are shown in Figure 6 when the input power of the HR-WPT system is 1 W. SAR_{10g} indicates the average localized SAR of any cubical volume of tissue equivalent to 10 g. SAR_{wb} indicates the average SAR of a whole-body. The ICNIRP guidelines recommend that SAR_{wb} does not exceed 0.08 W/kg and SAR_{10g} does not exceed 2 W/kg for the head and the trunk, and 4 W/kg for limbs. Thus, the results indicate that, in all cases considered, the SARs computed comply with the ICNIRP guidelines at the 1 W input power. The highest localized SAR is found at muscle tissue in all cases.

In comparison to the misalignment situations, the SAR computed in alignment is low. This is because the electric and magnetic fields in the misalignment conditions are strongly distributed in a larger area than those in the alignment condition, as shown in Figures 4 and 5, to achieve the best power transfer efficiency. Of the exposure scenarios in the misalignment condition, the SAR of Case 3 is the worst. Figure 7 shows the SAR distributions for Case 1 and Case 3 in a logarithmic scale, as respective representatives of alignment and misalignment conditions. The values of SAR for both Cases 1 and 3 are strongly distributed in the lower half of the body because the HR-WPT system is in front of the feet. However, the values of SAR calculated for Case 1 are slightly lower than those for Case 3 in correlation with the SAR results shown in Figure 6. Figure 8 shows the SAR distributions for Cases 1 and 3 in a linear scale to compare the two cases more clearly. In addition, Figure 9 shows the SAR distributions in the lower half of the body, for Cases 1 and 3 in a logarithmic scale. It can be confirmed that the SAR for Case 3 which is representative of misalignment is more strongly distributed than for Case 1, which is representative of alignment.

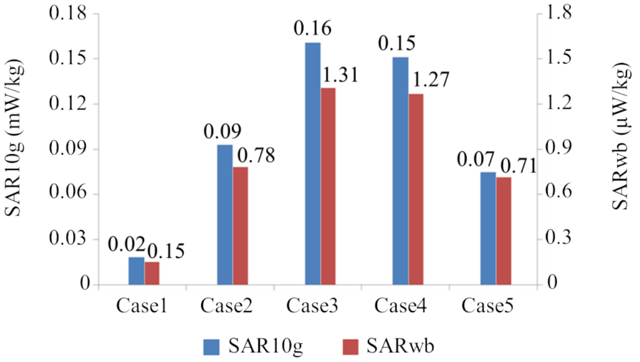
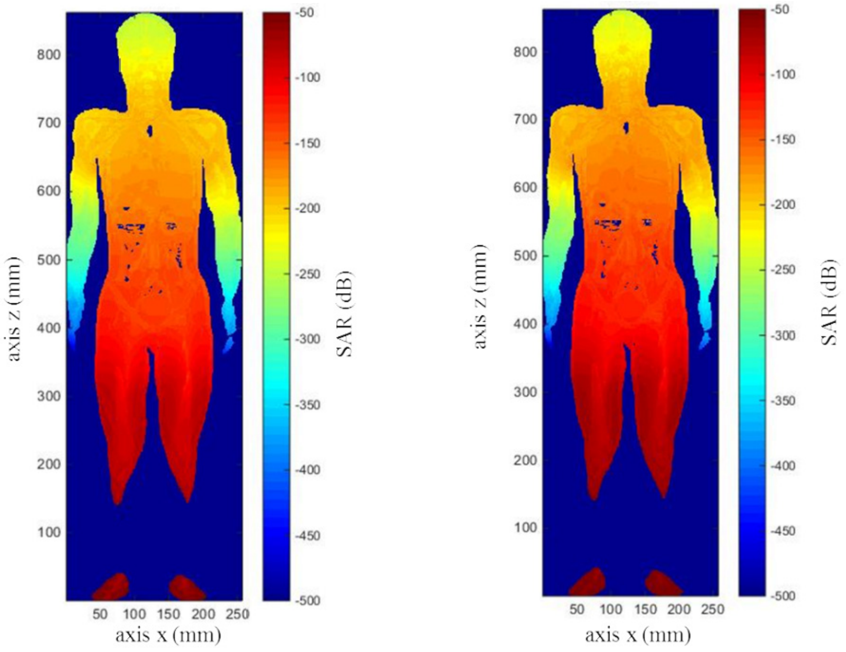


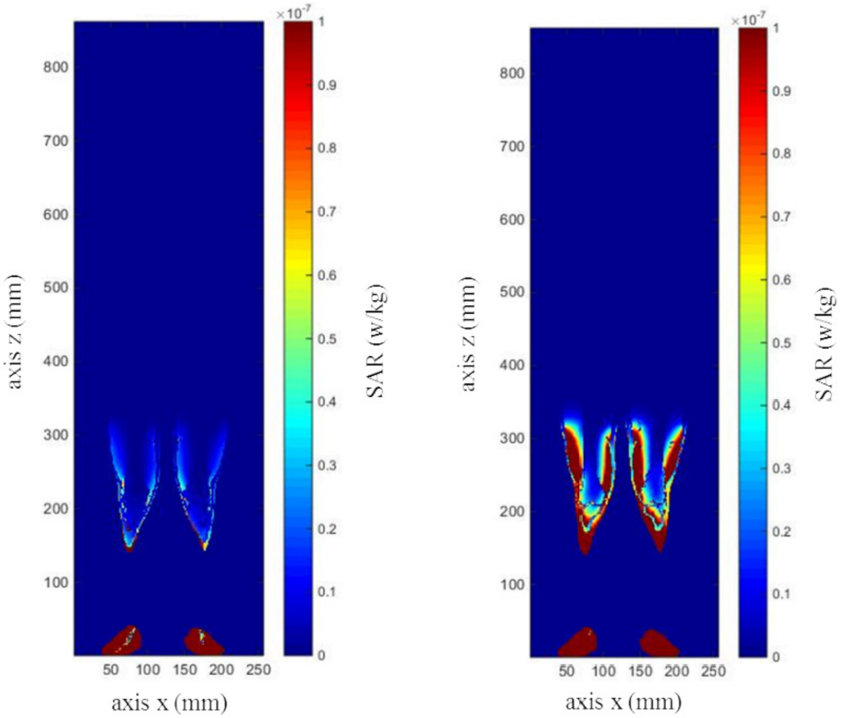
Figure 6. Localized SAR and whole-body SAR for alignment (Case 1) and misalignment Cases (Case 2–Case 5).

The maximum allowable powers (MAPs) to comply with the ICNIRP guidelines are investigated for the five exposure scenarios as shown in Figure 10. The results show that the MAPs for the misalignment cases are lower than the MAP for the alignment case. The MAPs for Case 1, which



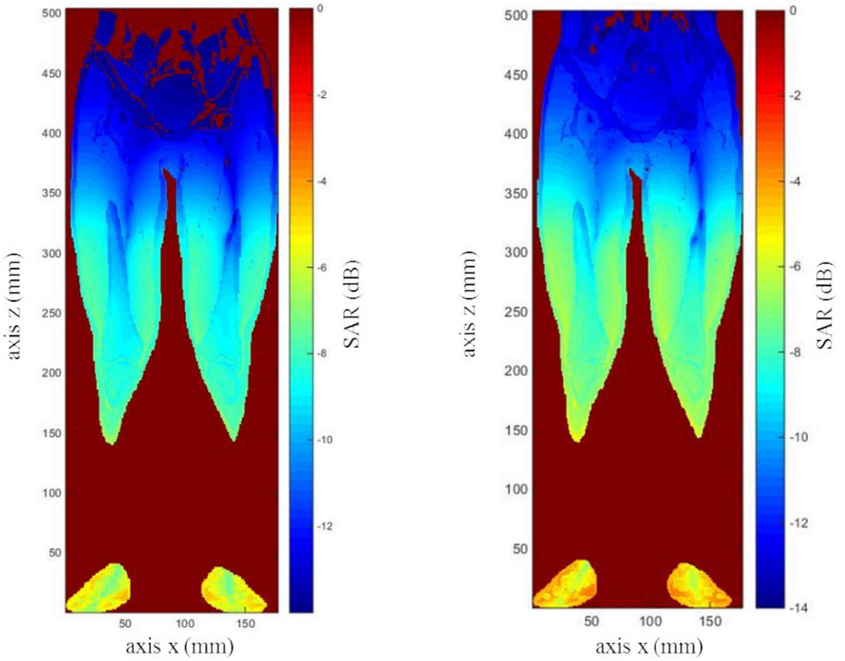
(a) (b)

Figure 7. SAR distributions (logarithmic scale) in the xz plane for the representative (a) alignment (Case 1), and (b) misalignment (Case 3) conditions.



(a) (b)

Figure 8. SAR distributions (linear scale) in the xz plane for the representative (a) alignment (Case 1), and (b) misalignment (Case 3) conditions.



(a) (b)

Figure 9. SAR distributions (logarithmic scale) for the representative (a) alignment (Case 1), and (b) misalignment (Case 3) conditions. Only the lower half of the body is considered in this figure.

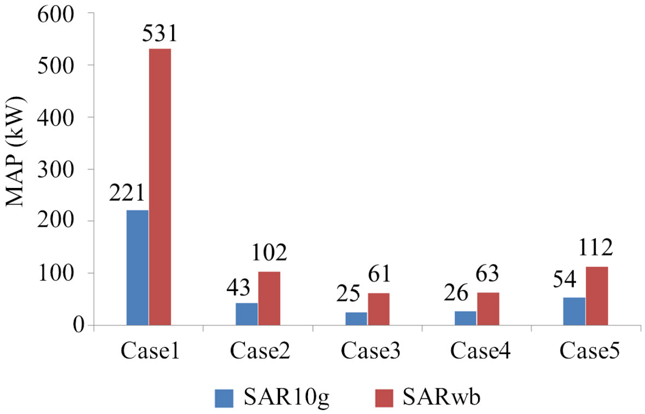


Figure 10. Maximum allowable power to comply with the ICNIRP guidelines for the five exposure scenarios considered.

is the alignment condition are 221 kW and 531 kW for SAR_{10g} and SAR_{wb}, respectively. In contrast, the MAPs of Case 3, which is the worst of the misalignment conditions, are 25 kW and 61 kW for SAR_{10g} and SAR_{wb}, respectively. The respective MAPs for the alignment and misalignment conditions to comply with the ICNIRP guidelines are 221 kW and 25 kW, respectively. Therefore, the MAP for the misalignment condition is 8.84 times lower than for the alignment condition. These results suggest that the misalignment of the HR-WPT system should be considered when conducting exposure assessment.

4. CONCLUSION

In this paper, a compact HR-WPT system was proposed. Analysis performed in this paper showed that the power transfer efficiency which is reduced when the alignment between the transmitting coil and receiving coil is changed could be compensated by adjusting the size of the feeding loop for matching. Dosimetry was conducted for the WPT considering the alignment and misalignment between the transmitter and receiver. The SARs in the misalignment conditions were higher than those in the alignment condition. The dosimetric results of the WPT system indicated that the worstcase exposure scenario generally occurred in the misalignment case.

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