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Bio-Electromagnetic Safety Assessment of Wireless Charging Environment for Electric Vehicles

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ABSTRACT: Wireless power charging technology has been developed rapidly and is extensively utilized for electric vehicle wireless charging due to its numerous over plug-in charging. Electromagnetic bio-safety of the human body in charging environment has become a significant public concern. To address this issue, this paper employs the finite element analysis method to assess the electromagnetic safety of crucial organs in a typical charging environment. Firstly, human-vehicle models in various typical postures were constructed in COMSOL, and the spatial distribution of electromagnetic fields in the critical organs was calculated in a 7.7 kW, 85 kHz charging environment. Subsequently, the electromagnetic radiation dose of each organ was calculated and compared with the ICNIRP standards. The results indicated that the electromagnetic radiation dose received by different organs is influenced by both the electromagnetic parameters and position of the organs. When the human body is positioned flat in the car, the electromagnetic radiation exposure to various organs is at its highest. Additionally, the maximum radiation dose for each organ is significantly below ICNIRP standard in a low-power wireless charging environment, supporting the commercial adoption of wireless charging technology for electric vehicles.

1. INTRODUCTION

With the rapid development of the world economy, energy waste and environmental pollution severely hinder the sustainable survival and development of humanity. Compared with traditional fuel vehicles, electric vehicles offer substantial economic and environmental benefits and significantly advance the energy revolution due to their zero pollutant emissions and higher energy utilization efficiency. At present, electric vehicle mainly uses plug-in connectors for charging, which suffer from several drawbacks, including reduced charging flexibility, the potential for spark discharge during insertion and removal, wear and tear with repeated use, and inconsistent international connector standards. These issues significantly constrain the popularization and development of electric vehicles. To address these problems, researchers are exploring wireless power transmission (WPT) to tackle the energy replenishment challenges of electric vehicles. WPT offers advantages such as high space utilization, enhanced safety, and ease of use compared to plug-in charging [1]. Therefore, wireless charging technology for electric vehicles shows promising application prospects [2, 3]. In wireless charging, the transmitting coil and receiving coil couple through a spatial magnetic field to achieve non-contact transmission of electrical energy. Therefore, the study of the safety of the electromagnetic environment for carrying living organisms has become crucial. In response to this issue, researchers and electric vehicle manufacturers have conducted a range of electromagnetic bio-safety tests and evaluations and established several electromagnetic safety assessment standards [4–6].

Asa et al. measured the magnetic induction intensity at the floor, seat, and headrest positions when the emission and reception coils of electric vehicles were misaligned, and the measurement results complied with the standards set by the International Committee on Non-Ionizing Radiation Protection [7]. The Cheonan Automotive Research Institute in South Korea simulated and calculated the electromagnetic field intensity when a person is positioned at the bottom of a car near the WPT system, finding that the induced electric field experienced by the human body exceeds the international standard limit. The industry standard "SAE TIR J2954", issued by the American Society of Automotive Engineers, establishes the standard frequency for wireless charging of light electric vehicles at 85 kHz, with a frequency range of 81.38 to 90.00 kHz. At present, among the important electromagnetic standards, representative ones include the ICNIRP-2010 standard of the International Committee on Non Ionizing Radiation Protection, the IEEE C95.1a-2010 guideline of the American Institute of Electrical and Electronics Engineers, and the GB8702-2014 specification of China's Electromagnetic Environment Control Limits [8–12]. Compared to other standards, ICNIRP comprehensively considers the adverse effects of electromagnetic radiation environment on public and occupational health. This article use ICNIRP as the reference standard.

This article uses a wireless charging system with a working frequency of 85 kHz as the research object and constructs a detailed human body model with internal organs, as well as a res-

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onator and vehicle body model equipped with metal plates. The electromagnetic radiation field of human body at various positions within electric vehicles and in different postures was calculated, and the electromagnetic radiation dose was evaluated. The simulation results were compared with the ICNIRP standard to analyze the safety of human bodies in this electromagnetic environment. The simulation results showed that different organs in the human body absorbed electromagnetic waves differently due to their various shapes and electromagnetic parameters. This was particularly evident when people sit and stand, and the calculated electromagnetic indicators of each organ have relatively large differences. The research results of this article serve as a basis for developing electromagnetic standards in China.

2. PRINCIPLES OF ELECTROMAGNETIC EXPOSURE CALCULATION

The basic limit of radio frequency electromagnetic exposure standards is determining the physiological response of the human body to electromagnetic fields, mainly measured by specific absorption rate (SAR) [9]. SAR represents the electromagnetic power absorbed by a unit mass of biological tissue, which is currently recognized in the academic community as the electromagnetic radiation dose [13]. The SAR value can be calculated by the following formula.

$$\text{SAR} = \frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\mathrm{d}W}{\mathrm{d}m}\right) = \frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\mathrm{d}W}{\rho \mathrm{d}V}\right) \tag{1}$$

where W is the total electromagnetic energy absorbed by human tissues, t the time, m the quality of biological tissue, ρ the mass density of biological tissue, and V the volume of biological tissue.

The values of SAR and current density in different parts of the human body are difficult to obtain directly through experimental methods, and electromagnetic simulation is more efficient for modeling and obtaining electromagnetic field characteristics than experimental measurements. Therefore, this article employs theoretical electromagnetic dose assessment method to simulate and calculate their values.

Because the temperature rise of human organs affected by thermal effects is difficult to measure and shows minimal variation, and the specific absorption rate is primarily reflected in the form of heat, the SAR value of human organs is a more accurate measure of the thermal effect of radiation on the human body in this electromagnetic environment, making it a key index for electromagnetic safety calculations . This article calculates the average SAR (signed as "SARa") of important organs in the human body based on the equation as follows.

$$\text{SARa} = \frac{\sigma \left|E\right|^2}{\rho} = C\frac{\mathrm{d}T}{\mathrm{d}t} \tag{2}$$

where C represents the specific heat capacity of human tissue [8], in units of J/(kg · k); $\mathrm{d}T/\mathrm{d}t$ represents the rate of change in human tissue, expressed in K/s; E represents the effective value of the space electric field; σ represents the conductivity of human tissue, in S/m.

3. HUMAN SAFETY ASSESSMENT IN ELECTRIC VEHICLE SIMULATION ENVIRONMENT

3.1. Wireless Charging System Model for Electric Vehicles

During the wireless charging process of electric vehicles, wireless energy transmission is achieved by coupling the transmitting coil installed on the ground with the receiving coil located on the car chassis. Therefore, the electromagnetic environment around the system is not only affected by the coupling of the wireless energy transmission coil itself but also influenced by external factors such as the surrounding environment, vehicle body, and chassis. To simulate this environment, resonators and car models were created in the COMSOL simulation system. The resonator coil adopts a magnetic shielding ferrite structure and is equipped with a matching metal plate to simulate the car chassis. The coil structure dimensions of the receiving and transmitting ends are the same, and the system parameters are shown in Table 1.

TABLE 1. Simulation coil parameters.

Parameters	Value
Inner size (m)	$0.4 * 0.2$
Outer size (m)	$0.8 * 0.6$
resonant frequency (kHz)	85
Power (kW)	14.6
Magnetic shielding plate size (m)	$0.8 * 0.6 * 0.01$
Axial distance between two coils (m)	0.12
Coil diameter (m)	$1.13e-3$
Automotive chassis dimensions (Length * width * thickness (m))	$4.8 * 1.6 * 0.01$
Number of turns	11

Build a simple car body model, referring to the design of domestic standard car models, with a size of 4.6 m × 1.8 m × 1.5 m. Set the electromagnetic properties of automotive materials, and the car simulation model is shown in Fig. 1.

3.2. Simulation Model for Human Body

To evaluate the electromagnetic safety of the human body in the wireless charging radiation environment of electric vehicles, a simplified model of important human organs was designed using simulation software. The main focus was on studying the effects of electromagnetic radiation in this environment on the brain, heart, liver, spleen, lungs, and kidneys. The SAR values for important sensitive organs were calculated at different positions and postures, such as people sitting in the driver's seat, lying flat inside the car, and standing outside the car near the circles. The electromagnetic parameters of each organ are set in Table 2 at a frequency of 85 kHz, based on the normal range values from relevant literature [10]. The three-dimensional simulation model of the human body is shown in Fig. 2.

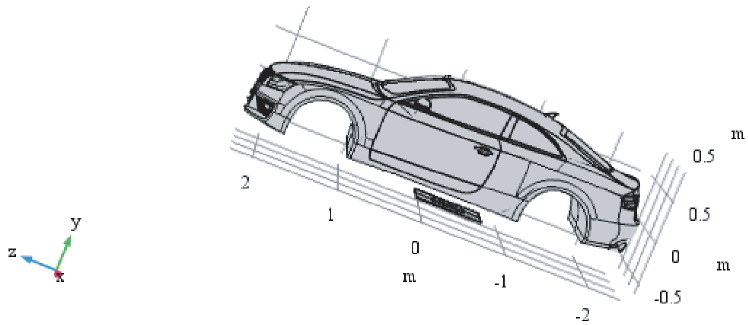

FIGURE 1. Car simulation model.

TABLE 2. Human organ parameter table.

Organ name	Relative permeability	Relative dielectric constant	Conductivity (S/m)
lung	1	5011.87	0.158
kidney	1	7126.4	0.179
liver	1	11294.6	0.113
heart	1	8500	0.316
brain	1	2804	0.129
spleen	1	10000	0.113

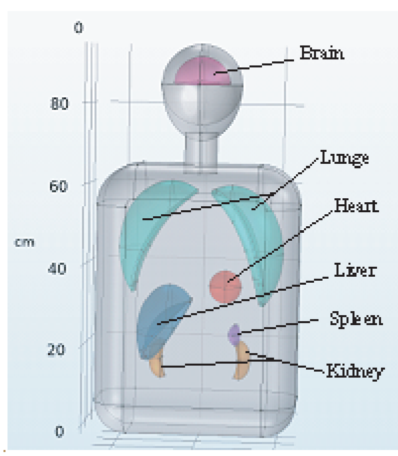

FIGURE 2. 3D simulation model of human organs.

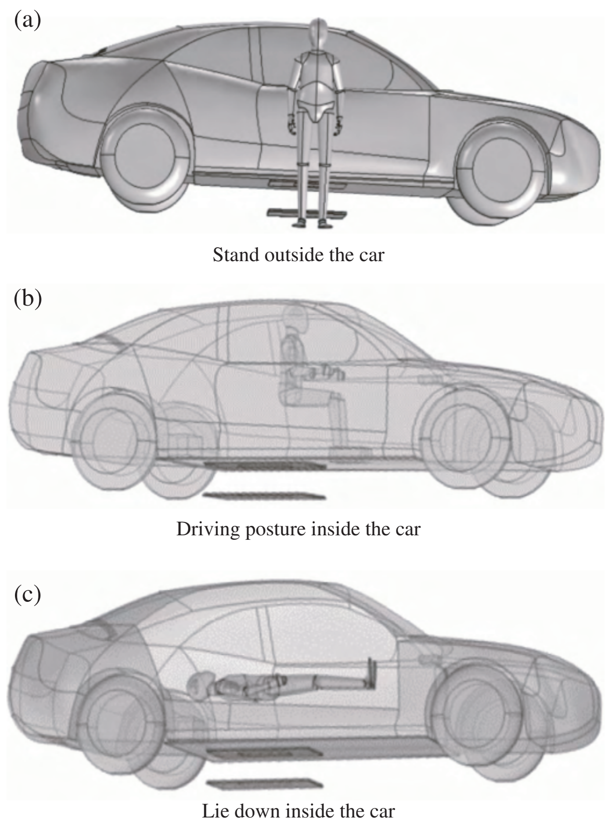

FIGURE 3. Human and automotive system in wireless charging electromagnetic environment.

3.3. Analysis of the Impact of Wireless Charging on Human Body

This article conducts research on the electromagnetic environment with a charging power of 7.7 kW, which is a relatively high charging power level for commercial electric vehicles. The electromagnetic safety of the human body was evaluated in a simulation environment, comprising cars and the human body in various postures and positions inside and outside the car, as shown in Fig. 3, including sitting in the driver's seat, lying on the rear seats, and standing on the ground outside the car, to evaluate the electromagnetic radiation safety indicators such as time average energy density, current density, and SARa value [8]. The basis for evaluating human electromagnetic safety in this article follows the ICNIRP 1998 standard.

The brain, heart, liver, spleen, lungs, and kidneys were selected for study, and the spatial distribution of induced current and magnetic field in each organ separately was analyzed separately, as shown in Fig. 4. From Fig. 4(a), it can be seen that there is a significant difference in the amplitude of the induced current in different organs in a sitting position. Among them, the brain has the smallest amplitude of the induced current due to its greater distance from the coil, while the kidney has the largest amplitude of the induced current. As shown in Fig. 4(b), the maximum and minimum values of magnetic flux density are

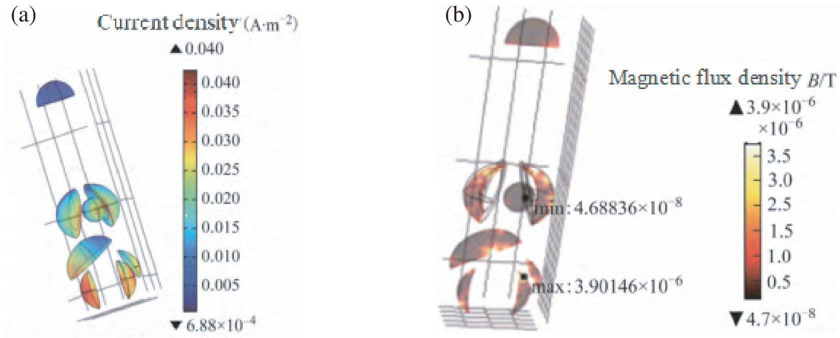

FIGURE 4. Calculation results of electromagnetic field of human organs at driving posture.

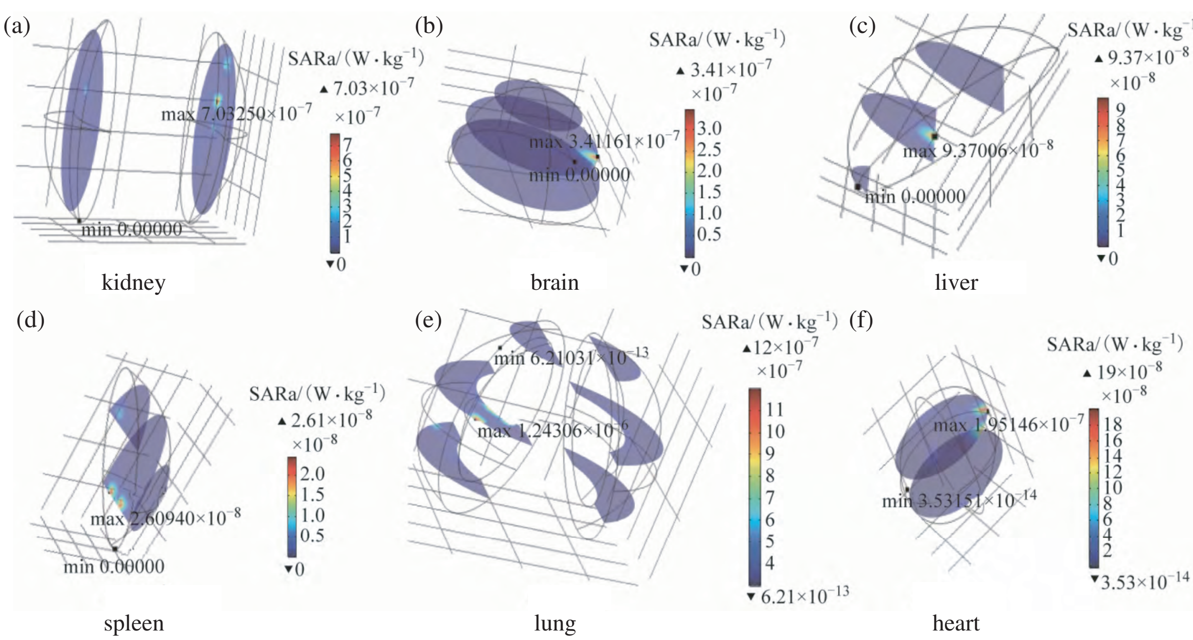

FIGURE 5. The 3D organ-section of the SARa maximum point.

located in the kidneys (3.9 μT) and heart (0.047 μT), respectively, with an amplitude difference about 80 times.

To study the thermal effects of radiation on the human body, the distribution of SARa values in various organs was calculated according to Eq. (1), and the maximum SARa value surface of each organ was extracted, as shown in Fig. 5.

The maximum SARa values, current density, and power density of each organ were calculated when the human body is in standing, sitting, or lying positions in the electric vehicle system, as shown in Fig. 6. It is evident that the human body is most affected by radiation when lying in the car, and its electromagnetic radiation value is significantly higher than that of standing and sitting positions. In sitting and standing positions, there is a significant difference in the same electromagnetic radiation safety index due to variations in organ shapes, electromagnetic parameters, and positions within the electromagnetic environment. However, in the lying position, due to the close distance between human organs and the charging coil at the bottom of the car, there is a small difference in the values of each organ for the same index. Due to the shielding effect of the car body and the increasing distance from the coil, the electromagnetic indicators of standing outside the car are slightly lower than those of sitting inside the car.

As shown in Fig. 6, the bar chart illustrates the electromagnetic radiation dose received by various organs of the human body for different postures. As shown in the figure, the electromagnetic radiation dose borne by various organs of the human body is influenced by the electromagnetic characteristic parameters of the organs and their positions. Among them, the electromagnetic radiation doses in the lying position inside the car were significantly higher than those in the sitting and standing positions. Due to the different shapes, electromagnetic parameters, and positions of different organs, there were significant differences for the same electromagnetic radiation safety index between sitting inside the car and standing outside the car. Furthermore, the electromagnetic radiation dose of all parts is much lower than the limit value of ICNIRP standard, as shown in Table 3, at the studied charging power. The electromagnetic exposure limits specified in the ICNIRP standard are shown in Table 1.

In summary, during low-power charging of electric vehicles, the electromagnetic radiation dose absorbed by various organs

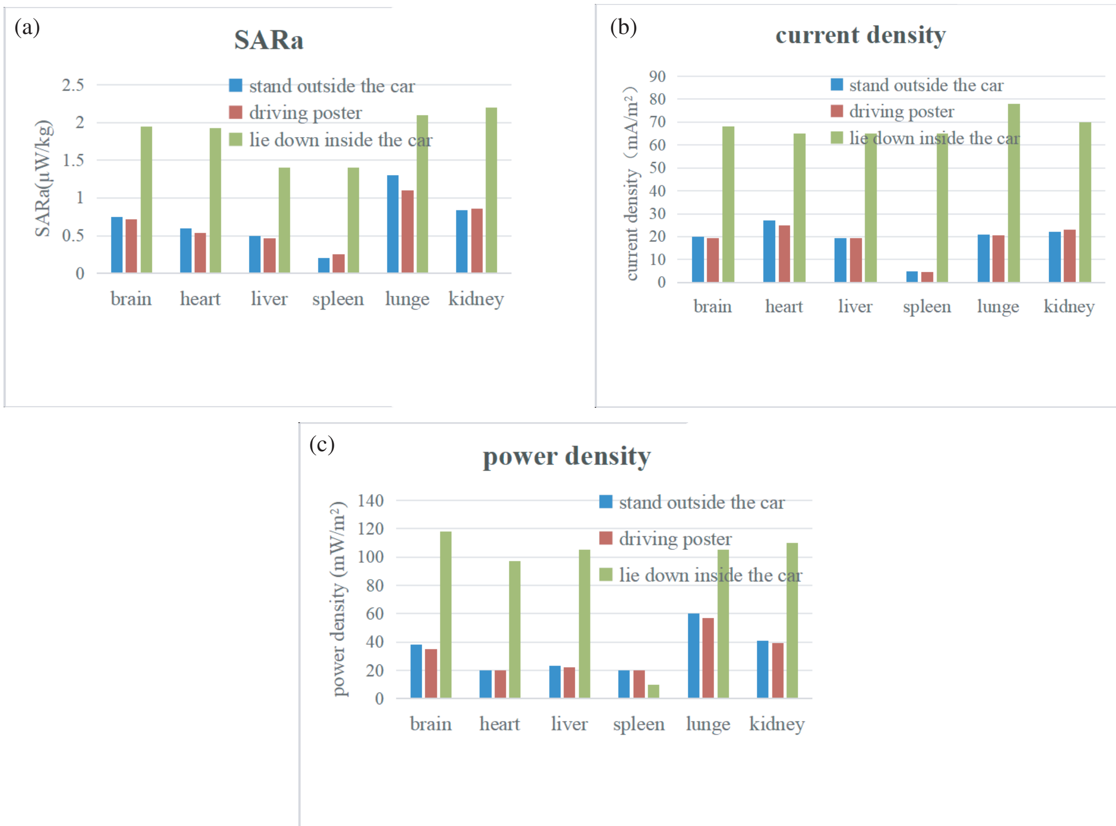

FIGURE 6. The maximum values of electromagnetic radiation parameter for organs.

TABLE 3. Electromagnetic exposure limits in the ICNIRP standard [14].

	ICNIRP for the public	ICNIRP for Occupational
SARa (W/kg)	2	10
Current density (mA/m^2)	f/200	f/100
Power density (W/m^2)	10	50

of the human body does not exceeded the limit. However, the disturbance caused by induced currents to neural activity in the brain may pose a risk of neurological degeneration and other diseases if the human body is exposed to electromagnetic radiation for extended periods. Therefore, when using electric vehicles for charging in daily life, individuals should ensure proper electromagnetic shielding of key radiation-sensitive organs. It is recommended that people minimize their time in the car, especially when lying down on the seat to rest during charging.

4. CONCLUSION AND PROSPECT

Regarding the electromagnetic radiation issue in wireless charging of electric vehicles, the electromagnetic safety of human body in wireless charging radiation environment for electric vehicles was assessed using COMSOL multi-physics finite element analysis software. Important internal organs of the human body were the focus of this research. The magnetic flux density, SARa, energy density, and power density were analyzed, and the spatial distribution of these parameters in organs was extracted. Maximum parameter plane diagram was created in this study. The simulation results indicated that the maximum values of various electromagnetic safety indicators studied are all below the ICNIRP safety limit under the low-power wireless charging electromagnetic environment of electric vehicles. When people stand outside the car or in a driving posture, there are significant differences in the same indicator, and the closer the organ is to the car chassis, the greater the electromagnetic radiation dose it receives. When people lie flat inside the car, the radiation dose received is the highest, and the differences in organ values are relatively small. With the increase power of wireless charging, the radiation dose absorbed by human organs will rise correspondingly, and some indicators may exceed the limit. Therefore, when high-power wireless charging systems are designed, electromagnetic shielding should be considered to reduce the impact of electromagnetic radiation on the human body. This provides a basis for the establishment of electromagnetic environment safety standards in China and promotes the commercialization of wireless charging technology for electric vehicles.

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