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Uncertainty Quantification of Electromagnetic Exposure Safety for Humans with Medical Implants in Electric Vehicle Wireless Charging Systems

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ABSTRACT

With the increasing adoption of electric vehicle (EV) wireless power transfer (WPT) technology, its electromagnetic environment and potential safety impacts on humans, particularly those with medical implants, have become a critical research concern. This study investigates the uncertainty in electromagnetic exposure safety within EV-WPT systems through systematic modeling and quantitative analysis. First, an EV-WPT system model including the vehicle, transmitting/receiving coils, and ferrite shielding layer was constructed, while a human body model with key organs (brain, heart, lungs, etc.) and a coronary stent was developed using COMSOL finite element simulations. Second, Gaussian Process Regression (GPR) was introduced to quantify uncertainties in the maximum induced electric field within the human body, considering variations in coil lateral offset, vertical offset, coil spacing, and human position. Results show that under these uncertainties, there is a 32.5% probability that the maximum induced electric field exceeds the ICNIRP 2010 safety limit (11.5 V/m), with significantly higher risks when the human body is located outside the vehicle. This research provides theoretical guidance for electromagnetic safety protection design in EV-WPT systems and offers important implications for ensuring charging safety in populations with medical implants.

KEYWORDS

Electric Vehicle; Wireless Power Transfer; Gaussian Process Regression.

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1. INTRODUCTION

In recent years, the global oil energy crisis and environmental pollution have become increasingly severe. In order to reduce the dependence of traditional cars on petroleum fuels, new energy driven vehicles continue to emerge and evolve with the development of the times. Compared with traditional cars, electric vehicles have shown significant advantages in reducing exhaust pollution and improving energy efficiency, thus playing an irreplaceable role in environmental protection and energy conservation [1]. At present, the charging methods of electric vehicles mainly rely on charging stations, charging piles, and battery replacement, but these methods still have many problems in terms of environmental adaptability and ease of use. With the continuous increase in the market share of electric vehicles, how to achieve safe and convenient charging of electric vehicles has become one of the main bottlenecks in its popularization process [2]. Wireless Power Transfer (WPT) is a technology that achieves wireless transmission of electrical energy through non-contact means, utilizing the propagation characteristics of electromagnetic waves in space [3].Applying this technology to the field of wireless charging for electric vehicles not only provides real-time wireless charging for stationary or moving electric vehicles, but also greatly improves charging convenience; At the same time, it can effectively solve the problem of sparks and wear on the power connector during wired charging, significantly improving charging safety [4]. Therefore, wireless charging technology for electric vehicles has become an important direction in the research field of wireless energy transmission technology.

With the continuous advancement of wireless charging technology for electric vehicles and its promotion in practical applications, electromagnetic environment safety and its potential impact on human health have become increasingly a research focus. At the same time, given the large number of individuals in society who rely on implantable medical devices to maintain their daily lives, such as heart stents, cochlear implants, artificial organs, etc., the electromagnetic exposure safety issues of these devices in wireless energy transmission electromagnetic field environments urgently need to be further explored. D. Sarah and her research team conducted a study on whether cardiovascular implanted electronic devices are susceptible to mid frequency (1kHz~1MHz) electromagnetic interference. The results showed that the influencing factors of electromagnetic interference have not been fully defined and described [5]. Reference [6] exposed the implanted cardiac device to the electromagnetic field of a colonoscopy magnetic imaging device (Scope Guide) and analyzed whether there was electromagnetic interference. The study found that the electromagnetic field of Scope Guide does not cause interference, so it may be safe to use it in patients with implanted cardiac devices.

However, considering the uncertainty in the production, manufacturing, installation, and other processes of the EV-WPT system, as well as the uncertainty caused by changes in human body position around the WPT system in real life, it can spread to the human electromagnetic exposure dose of the EV-WPT system, especially when the human body is located outside the vehicle, posing greater risks to human electromagnetic exposure safety. Therefore, it is of great significance to study the uncertainty of electromagnetic exposure safety of EV-WPT systems with medical implants in the human body.

The main research content of this article is as follows: In the second section, an EV-WPT system model was established considering practical application situations. Considering ethical issues in medicine, a model of the human body and some important organs was established, and a coronary stent model was also established; The third section introduces Gaussian process theory for uncertainty quantification analysis of human electromagnetic exposure safety; The fourth section presents the quantitative results of the uncertainty of human electromagnetic exposure safety in the EV-WPT system and analyzes them; The fifth section summarizes the research content of this article.

2. ESTABLISHMENT OF EV-WPT SYSTEM, HUMAN BODY, AND MEDICAL IMPLANT MODELS

2.1 EV-WPT System Model

The EV-WPT system model for research on human electromagnetic exposure consists of three parts: the electric vehicle (EV), the transmitting system, and the receiving system. Fig. 1 (front view) shows the relative position of the vehicle-human model. The EV model is constructed based on the geometric shape of actual vehicles, with dimensions of 4000×2000×1500 mm (length × width × height), which is close to the geometric parameters of commercial EVs and can serve as a research model for electromagnetic numerical simulation.

Considering the accuracy of numerical simulation and the requirements of actual EVs for lightweight, high rigidity, and stability, the vehicle body and wheel hubs are made of aluminum, the tires are made of rubber, and the front and rear windshields and windows are made of tempered glass. The WPT system adopts a dual-coil resonant structure based on electromagnetic resonance technology and the WPT system is 11kW. The coils are made of disc-shaped copper, with the transmitting coil (Tx) and receiving coil (Rx) having 15 turns and 12 turns respectively, and their cross-sectional areas are 3×10^{-6} mm^2 and 2×10^{-6} mm^2 respectively. To reduce electromagnetic field leakage during charging of the EV-WPT system, a square ferrite shielding layer is used, with dimensions of 650×650×10 mm (length × width × height). The relative permeability of the ferrite material of the shielding layer is 2500, and its electrical conductivity is negligible. The WPT system adopts an SS compensation structure.

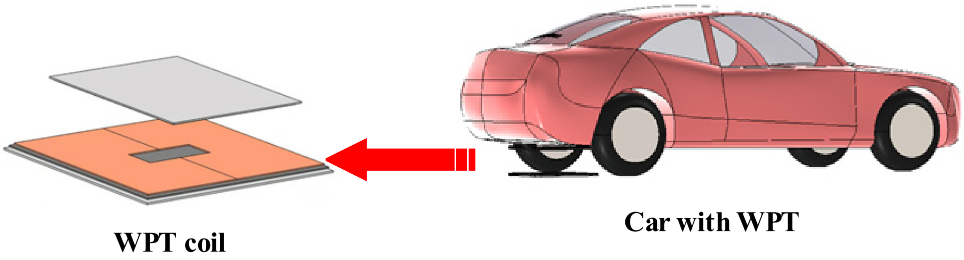
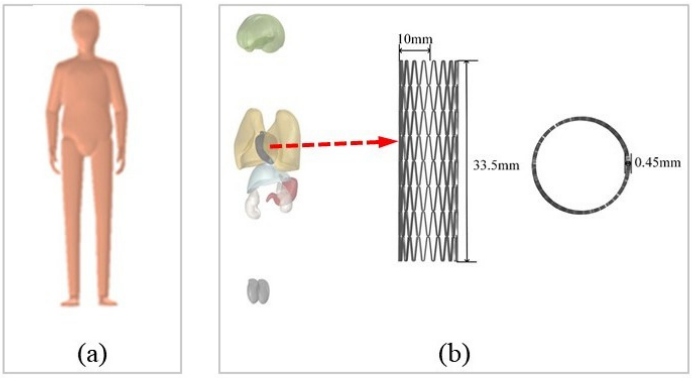


Fig 1. EV-WPT system model

2.2 Human Body and Organ Models

To accurately quantify the electromagnetic exposure of the standing human body under the leaked electromagnetic fields generated by the EV-WPT system, this paper uses the commercial finite element software COMSOL to process the human body model and implants, achieving electromagnetic simulation of the standing human body with implants, as shown in Fig. 3. Meanwhile, considering that different organ tissues of the human body with medical implants are of great significance to the accuracy of human electromagnetic safety assessment, the same method is used to establish organ models of the human brain, heart, lungs, kidneys, stomach, and liver, as shown in Fig. 2.



(a) The standing human model (b) Human organs and Cardiac stent implantation model

Fig 2. Human organ models and implants

3. PRINCIPLE OF GAUSSIAN PROCESS REGRESSION

GPR can select different covariance functions. A commonly used covariance function is the squared exponential covariance,It can be seen from the above formula that the inversion of an $n\times n$ matrix has been transformed into the inversion of an $m\times m$ matrix. The training computation has been reduced from $O(n^3)$ to $O(n^2m)$, and the prediction computation has been reduced from $O(n^2)$ to $O(m^2)$. However, how to realize $K_n = VV^{\mathrm{T}}$ is the key to this method. The method of using eigenvalue decomposition and then retaining m dominant eigenvalues can realize this step, but since the computation of eigenvalue decomposition for K_n in general cases is also as high as $O(n^3)$, this method is not applicable. Therefore, efficient (with small computation) approximate eigenvalue decomposition methods can be adopted, among which the Nyström method is widely used.

Similar to the SD approximation method, the Nyström approximation method selects a subset with dimension m from the original training set, called the inclusion set or active set, then K_n can be decomposed into modules as

$$K_n = [\begin{matrix} K_{mm} & K_{m(n-m)} \\ K_{(n-m)m} & K_{(n-m)(n-m)} \end{matrix}] \tag{1}$$

The $m \times n$ block at the top of the above formula is denoted as K_{mn} (its transpose is K_n). Using the Nyström method to construct K_n, an approximate covariance matrix $\tilde{K}_n = K_{nm} K_{mm}^{-1} K_{mn}$, is obtained. At this time, the computation of $O(m^2 n)$. It can also be obtained that:

$$\begin{aligned} K_{mm} &= \tilde{K}_{mm} \\ K_{m(n-m)} &= \tilde{K}_{m(n-m)} \\ \tilde{K}_{(n-m)(n-m)} &= K_{(n-m)m} K_{mm}{}^{-1} K_{m(n-m)} \\ K_{(n-m)m} &= \tilde{K}_{(n-m)m} \end{aligned} \tag{2}$$

Let $k_m(\mathbf{x}) = \left[k(\mathbf{x}, \mathbf{x}_1), \cdots, k(\mathbf{x}, \mathbf{x}_m)\right]^{\mathrm{T}}$, $\tilde{k}(\mathbf{x}, \mathbf{x}') = k_m(\mathbf{x})^{\mathrm{T}} K_{mm}^{-1} k_m(\mathbf{x}')$. Williams et al. directly replace K_n with $\tilde{K}_n$ in formulas (2) and (3), and this method is called the Nyström approximation method for GPR. Its training computation is reduced to $O_{(m^2 n)}$, and the computation for mean and covariance prediction of a single test sample is reduced to $O_{(n)}$ and $O_{(mn)}$ respectively.

4. ANALYSIS RESULTS

In this section, the GPR algorithm introduced in Section 3 is utilized to quantitatively assess the safety of electromagnetic exposure in humans with coronary artery stent implants. Firstly, the electromagnetic exposure dose to the human body under fixed conditions is calculated using multiphysics simulation software, resulting in Figure 3. The legend used for the heart section is a separate legend, which is therefore significantly enlarged.

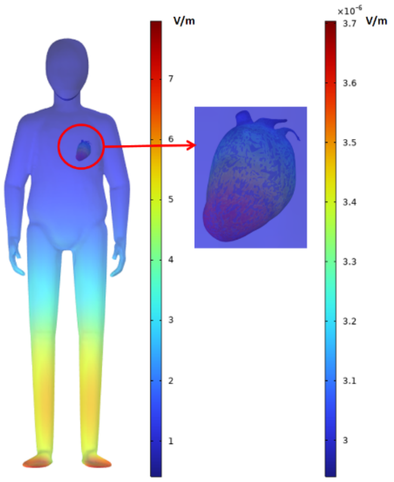


Fig 3. Distribution of induced electric field intensity in the human body under fixed conditions

As can be seen from Figure 3, the induced electric field intensity is more pronounced near the WPT position. Furthermore, considering uncertainty, the maximum induced electric field intensity within the human body is taken as the output variable, with coil lateral offset, coil longitudinal offset, coil spacing, and changes in human body position as the input variables. The distribution types and parameters of the input variables are shown in Table 1.

Table 1. The distribution types and parameters of the input variables

Variable	Distribution	Parameter/mm
Coil Lateral offset	Uniform	[-100，100]
Coil Vertical offset	Uniform	[-100，100]
Distance between coils	Uniform	[-20，20]
Human lateral displacement	Normal	[-200，200]
Human lateral displacement	Normal	[-200，200]

Using the GPR introduced in Section 3, we conducted an uncertainty quantification calculation for the maximum induced electric field strength in the human body. The results are shown in Figure 4. As can be seen from Figure 4, when a person is seated outside the vehicle, there is a possibility of exceeding the standard limit (11.5V/m) specified in ICNIRP2010, and the probability of exceeding the limit is 32.5%. This poses a significant electromagnetic exposure risk. Therefore, it is of great significance to conduct research on the protection of human electromagnetic exposure safety issues in EV-WPT systems.

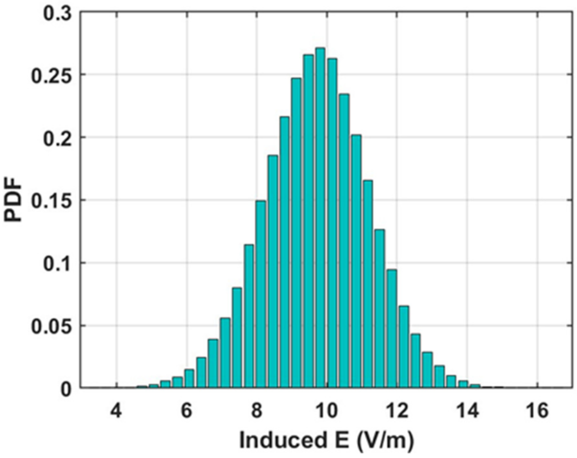


Fig 4. Probability density function of the maximum value of human-induced electric field intensity

5. SUMMARY

This study focuses on the uncertainty of electromagnetic exposure safety for humans with medical implants in EV-WPT systems. The EV-WPT system model (including transmitting/receiving coils and ferrite shielding), human body and organ models, and a coronary stent model were successfully established, laying the foundation for exposure simulation analysis. Uncertainty quantification using Gaussian Process Regression (GPR) revealed that coil misalignment, coil spacing, and human position variations cause significant fluctuations in the maximum induced electric field. Risk assessment further indicated that when the human body is outside the vehicle, the probability of exceeding the ICNIRP 2010 safety limit of 11.5 V/m reaches 32.5%, posing a considerable exposure risk. These findings clarify the sources and magnitudes of uncertainty in electromagnetic safety, providing essential references for optimizing system design and developing protective measures to reduce risks for individuals with medical implants, thereby supporting the safe deployment of EV-WPT technology.

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