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Wireless Power Transfer for Electric Vehicles and Electromagnetic Safety in the Human Body: A Review

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Abstract

With the rapid development and expansion of the electric vehicle industry, wireless power transfer technology, as a critical and final component within the intelligent autonomous driving technology system, is seeing its significance and application prospects become increasingly prominent, attracting widespread attention from both society and industry. However, as this technology moves towards industrialization, the issue of human electromagnetic safety has emerged as a primary task and core challenge demanding urgent resolution. This paper aims to comprehensively summarize and analyze the latest developments in both wireless power transfer technology and human electromagnetic safety technology. It delves into the biological effects and potential impacts of prolonged human exposure to low-frequency electromagnetic fields. Furthermore, the paper provides a detailed analysis of the status of existing relevant standards and their scientific basis. Additionally, it offers a forward-looking perspective on the future development trends of the human electromagnetic safety industry, exploring how technological innovation and policy guidance can effectively safeguard public health and promote the safe and efficient application of wireless power transfer technology.

Keywords

Electric Vehicles (EVs); Wireless Power Transfer (WPT); Human Electromagnetic Safety.

1. Introduction

The Sustainable Development of the Current Global Economy Relies Heavily on the Energy Revolution and Optimal Resource Allocation [1]. With increasing global emphasis on environmental protection and sustainable development, new energy electric vehicles (EVs)-as a green and eco-friendly transportation solution that replaces traditional fossil fuels with electricity-have received significant policy support and prioritized promotion in many countries. The industry continues to expand, and related smart charging technologies are gradually becoming a focal point in the sector. Against this backdrop, wireless power transfer (WPT) technology has rapidly emerged as a key alternative charging method due to its high safety, flexibility, and other advantages [2]. However, the widespread adoption of this technology still faces challenges, particularly concerning electromagnetic environmental safety, which requires further research and refinement. To address these concerns, scholars worldwide have conducted extensive research on low-frequency magnetic field exposure in EVs. Through a systematic review of measurement and simulation studies under specific exposure scenarios, this paper aims to identify the main factors influencing in-vehicle magnetic field distribution, characterize magnetic flux density patterns, analyze spectral properties, and establish methods for estimating human exposure doses. Building on these findings, we highlight critical unresolved issues in this field.

This paper focuses on the impact of low-frequency electromagnetic fields (EMFs) generated during EV wireless power transfer on human health, with an emphasis on systematically summarizing electromagnetic bio-safety concerns. First, we comprehensively review the latest advancements in EV wireless power transfer technology and elucidate the mechanisms behind low-frequency EMF generation. Second, we summarize the development and current applications of computational human models in bioelectromagnetics while organizing existing electromagnetic safety assessment standards to provide a reference for future research. Finally, we delve into the biological effects of low-frequency EMFs and their potential health implications, offering scientific insights to guide further research and protective measures.

2. Wireless Power Transfer Technology for Electric Vehicles

Currently, the contactless charging technology adopted by electric vehicles-wireless power transfer technology-is gradually becoming a focal point in the industry. Compared with traditional charging methods, wireless power transfer for electric vehicles demonstrates superior advantages, including higher space utilization efficiency, enhanced safety performance, and significantly reduced equipment wear [3]. From a theoretical perspective, this technology achieves a fully insulated design, supports flexible and convenient charging at any time, reduces reliance on battery capacity, and enables fully automated and intelligent charging processes [4]. It effectively addresses key challenges such as insufficient battery capacity, prolonged charging times, and the operational complexity of plug-in charging. The application scenarios for WPT are extensive. It can meet the fixed charging demands of static parking spaces while also enabling dynamic energy replenishment during vehicle movement through embedded roadway systems. This technology holds significant importance for advancing the new energy industry and supporting China's smart grid and energy internet strategies.

As an innovative charging solution, wireless power transfer technology has emerged as a critical driver of global technological innovation and a major research focus, accelerating the adoption of wireless power transfer for electric vehicles. Internationally, technical standards such as Qi, A4WP, and PWM have been updated to accommodate these advancements.

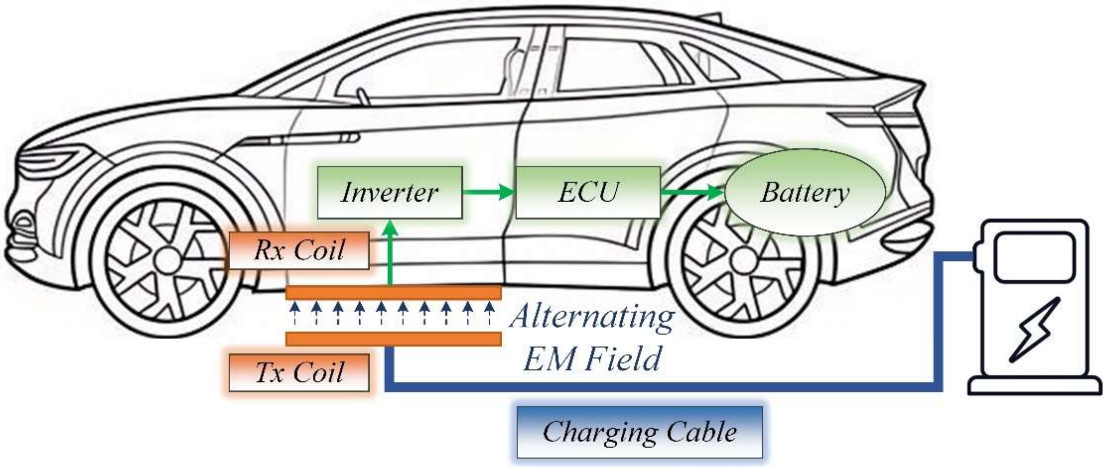

Fig. 1 Wireless power transfer technology for electric vehicles

Furthermore, with the continuous rise in market penetration of electric vehicles, concerns over electromagnetic exposure risks have grown significantly. Compared to traditional internal combustion engine vehicles, EVs are equipped with a greater number of electronic components, including in-vehicle DC power cables, traction battery packs, drive motors, high-voltage wiring harnesses, DC/DC converters, inverters, as well as external charging stations (both wired and wireless) and GPS communication antennas [5, 6]. When operating under high-voltage and high-current conditions for extended periods, these components generate complex electromagnetic fields, constituting primary sources of electromagnetic radiation [7, 8]. Given the confined and enclosed nature of vehicle cabins, occupants remain in close proximity to these radiation sources during operation. Prolonged exposure to such complex electromagnetic environments may pose potential health risks [9, 10]. Consequently, systematic analysis of in-vehicle electromagnetic environments and safety assessments of radiation sources carry substantial practical significance for safeguarding occupant health.

3. Numerical Simulation and Human Dosimetry Studies

Currently, constrained by measurement techniques and equipment dimensions, in-vehicle magnetic field measurements can only be conducted through limited point arrangements, making it difficult to fully characterize the spatiotemporal distribution characteristics of magnetic fields. Therefore, electromagnetic simulation has become a crucial approach for obtaining the overall distribution of low-frequency magnetic fields in electric vehicles. Commonly used numerical simulation methods include the Finite-Difference Time-Domain (FDTD) method, Finite Element Method (FEM), and Scalar Potential Finite Difference (SPFD) method. Numerical simulation has become a key reference for risk reduction in vehicle development [11].

Simulation studies have achieved significant results in magnetic shielding and material optimization: research has confirmed [12] that metal chassis can shield low-frequency magnetic fields from wireless power transfer systems, while fiber-reinforced composite chassis lack this capability; the use of shielding layers, horizontal shielding, and high-permeability ferromagnetic materials can effectively reduce magnetic field exposure, with improved ferromagnetic materials further reducing the magnetic field by 25%; rational selection of vehicle body materials is also an important approach to reducing occupant magnetic field exposure [13].

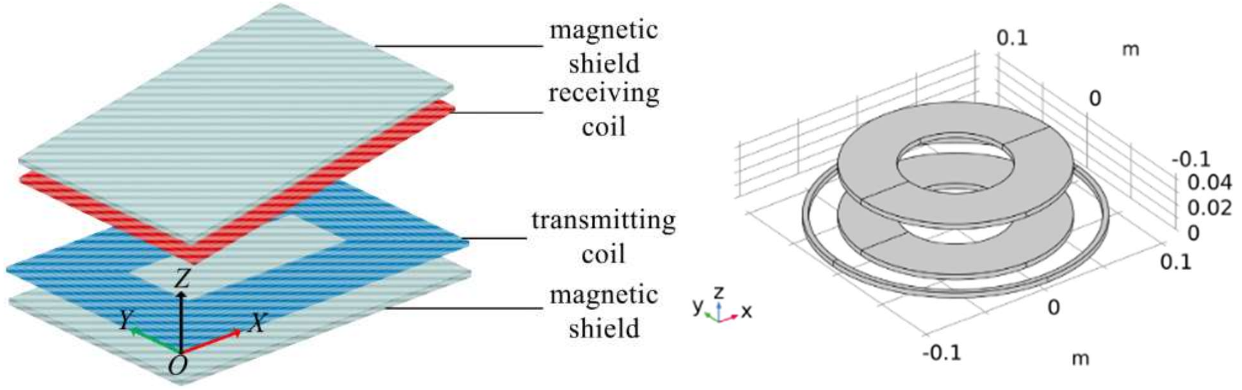

Fig. 2 Left: Common passive protection measures for coupling coils [13];
Right: Active protection measures [14]

Moreover, incorporating human body models into the simulation process enables the acquisition of physical quantities such as Specific Absorption Rate (SAR) and induced electric fields (E) [14] that are difficult to obtain through actual measurements, which facilitates the assessment of the effects of low-frequency magnetic fields on the human body [15]. Relevant studies indicate that although the magnetic flux density in certain areas is relatively high, it significantly attenuates with increasing distance, and the induced field strength mostly remains below the exposure limits. In simulations of wireless power transfer systems, peak values such as induced current density in internal organs are particularly prominent. Additionally, due to the physical characteristics of children, the induced electric field strength in their bodies is significantly lower than that in adults [16, 17, 18].

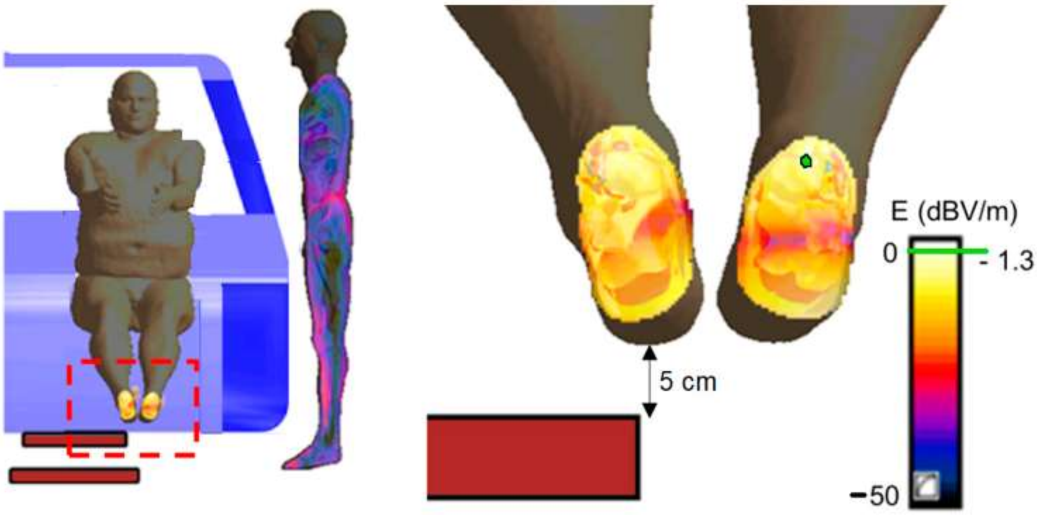

Fig. 3 Induced electric field distribution inside the anatomical human model Duke [19].

4. Impact of Biological Effects

Living organisms possess specific electromagnetic properties and exhibit bioelectromagnetic effects when exposed to electromagnetic radiation. The biological effects induced by electromagnetic radiation can be categorized into thermal effects, non-thermal effects, free radical chain reactions, and cumulative effects. Numerous research investigations have demonstrated that prolonged exposure to power-frequency electromagnetic fields and radiofrequency electromagnetic fields may cause symptoms such as dizziness, fatigue, and headaches in humans, and may even affect the health of the human body and central nervous system [20]. Research on the health effects of electromagnetic radiation originated from epidemiological studies, with a 1979 U.S. report first indicating higher cancer incidence among children living near power lines. Subsequent epidemiological surveys from multiple countries worldwide have confirmed that extremely low-frequency magnetic fields can adversely affect human health [21]. Occupationally exposed individuals show higher probabilities of developing malignant tumors, neurological disorders, and leukemia. The World Health Organization has classified extremely low-frequency electromagnetic fields as a possible human carcinogen [22]. Compared to hazards caused by air pollution or waste contamination, electromagnetic radiation is more abstract, omnipresent, and difficult to avoid [23]. With increasing electromagnetic interference, the spatial electromagnetic environment is becoming progressively more complex and hazardous, making electromagnetic exposure safety assessments and radiation protection measures critically important [24].

5. Electromagnetic Exposure Assessment Standards

Conducting electromagnetic exposure safety assessments for the in-vehicle electromagnetic environment of electric vehicles is essential. Both domestic and international bodies have established corresponding standards to investigate the worst-case exposure hazards and to define numerical and experimental evaluation methods. The most authoritative guidelines worldwide are ICNIRP 1998 [25], ICNIRP 2010 [26] issued by the International Commission on Non-Ionizing Radiation Protection (ICNIRP), and IEEE C95.1-1992 [27] and IEEE C95.1-2005

[28] published by the IEEE Standards Coordinating Committee. These safety guidelines introduce two distinct exposure limits: (1) basic restrictions and (2) reference levels, also known as maximum permissible exposure. Basic restrictions specify threshold values above which biological effects are expected to occur.

6. Summary

Overall, the electric vehicle industry is experiencing rapid global development, with technological advancements and growing environmental awareness leading to an increasing number of people choosing to drive and ride in electric vehicles. In this context, conducting comprehensive and detailed electromagnetic exposure safety assessments of the internal electromagnetic environment in electric vehicles becomes particularly crucial. Such evaluations can provide scientific recommendations for electric vehicle manufacturers to fully consider human electromagnetic safety during production, enabling them to implement effective measures and optimize designs to ensure higher safety standards regarding electromagnetic radiation. This approach not only helps safeguard the health and safety of drivers and passengers but also effectively promotes the healthy development of the electric vehicle industry, encouraging manufacturers to produce safer and more reliable electric vehicle products that gain greater market and consumer trust and preference.

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