Numerical EMI Estimation of Active Implantable Medical Devices for EV Wireless Power Transfer Systems Based on Induced Electric Field and Current in the Human Body

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ABSTRACT: This study presents a numerical evaluation of electromagnetic interference (EMI) affecting implantable pacemakers exposed to an 85 kHz wireless power transfer (WPT) system for electric vehicle (EV) charging. A human torso phantom model was employed to estimate the interference voltage induced at the pacemaker terminals by analyzing the coupling of electric and magnetic fields through FEM analysis. Multiple exposure scenarios were investigated by varying the phantom's position and orientation relative to the WPT system. The proposed methodology provides a robust framework for assessing EMI risks under conservative conditions and contributes to the design of safer WPT environments for individuals with implantable medical devices.

KEY WORDS: Wireless Power Transfer, Electromagnetic Interference (EMI), Implantable Cardiac Pacemaker, Finite Element Method (FEM), Human Body Phantom

1. INTRODUCTION

Wireless devices can generate electromagnetic interference (EMI) in nearby electronic equipment, raising particular concerns for implantable medical devices such as cardiac pacemakers and implantable cardioverter-defibrillators (ICDs). EMI in these devices poses a critical safety issue that demands thorough investigation [1-3]. In recent years, wireless power transfer (WPT) technology based on magnetic resonance coupling has gained significant attention, with promising applications for charging and powering various electrical systems and devices, including home appliances and electric vehicles (EVs) [4]. However, because these systems can generate strong reactive electric fields, it is essential to evaluate human exposure levels to ensure safety and compliance with regulatory standards. Previous studies have focused on compliance with fundamental exposure limits for human safety by examining induced currents and electric fields [5,6]. Despite these precautions, concerns remain that electromagnetic fields (EMFs) generated by WPT systems could interfere with pacemaker operation, particularly when patients with such devices are in close proximity to WPT equipment.

Typically, EMF strength decreases with increasing distance from the source. However, the EMF generated by WPT systems utilizing magnetic resonance coupling can be complex, as it is often influenced by coupling conditions such as frequency, air gap, and alignment [7,8]. These factors can cause fluctuations in EMF strength that do not always follow predictable attenuation patterns, raising additional concerns regarding interference with implantable medical devices. Accurately estimating the EMI risk zone for pacemakers and ICDs requires advanced numerical simulations and measurement techniques to ensure reliable risk assessments.

This paper introduces a case study in which a representative EV system equipped with 85 kHz magnetic coupling coils is combined with a human torso phantom to simulate realistic exposure scenarios [9, 10]. An example calculation of the interference voltage induced at the pacemaker's connector is presented, based on modeling the electric and magnetic field distribution within the human phantom using the finite element method (FEM). To conservatively estimate the maximum interference voltage, multiple exposure scenarios are analyzed by varying the orientation and position of the torso phantom relative to the WPT system. The proposed approach establishes a conservative framework for EMI risk assessment and provides actionable insights for the safe deployment of WPT systems in environments involving implantable medical devices.

2. NUMERICAL MODELING OF PACEMAKER EMI UNDER EV-WPT EXPOSURE

2.1. Pacemaker Phantom Modeling with Conservative Lead Configuration

To numerically estimate pacemaker EMI, a human torso phantom model, including an implantable cardiac pacemaker, was constructed, as shown in Fig. 1. The phantom consists of an acrylic tank filled with saline solution, replicating the setup used in experimental measurements. As illustrated, the pacemaker's ventricular electrode lead was modeled and connected to the pacemaker terminals, configured in a unipolar mode for this study. The interference voltage was evaluated using a 1 MΩ resistor. The dielectric constant and electrical conductivity of each material used in the phantom model are summarized in Table 1.

The pacemaker model employed in this study represents a single-chamber type pacemaker, with the lead configured in a unipolar mode. It is well known that, in the evaluation of electromagnetic interference (EMI) characteristics of pacemakers and implantable cardioverter-defibrillators (ICDs) in the low-frequency (LF) range, assessments under unipolar mode conditions tend to yield more conservative results, as EMI susceptibility is generally higher compared to bipolar mode configurations.

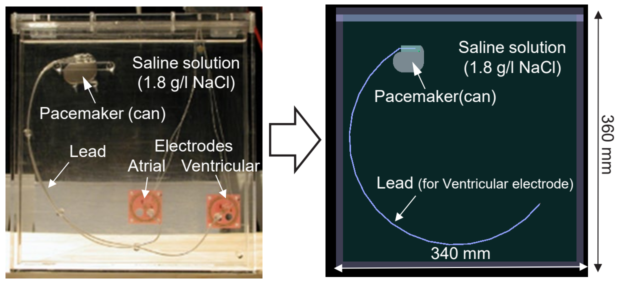
In addition, the length and routing of the lead were deliberately arranged to create a conservative EMI evaluation condition. The lead was modeled with a length of 58 cm and a layout that would maximize the coupling area exposed to the electromagnetic fields. This conservative approach was applied consistently in both the numerical simulation and experimental evaluation, ensuring that the EMI susceptibility of the pacemaker was assessed under worst-case conditions.

Table 1 Dielectric constant and electrical conductivity of materials used in the phantom model.

Material	ε_r	σ (S/m)
Pace maker, Lead	*Perfect electric conductor*	
Saline solution (1.8 g/l)	86.7	0.32
Silicon	2.7	0
Acrylic case	3	0

2.2. EV-WPT System Modeling and Exposure Scenarios

A detailed finite element model of an electric vehicle (EV) equipped with a wireless power transfer (WPT) system was developed to simulate electromagnetic interference (EMI) effects



Torso phantom for pacemaker EMI measurement

Numerical phantom model

Fig. 1. Numerical phantom for pacemaker EMI estimation.

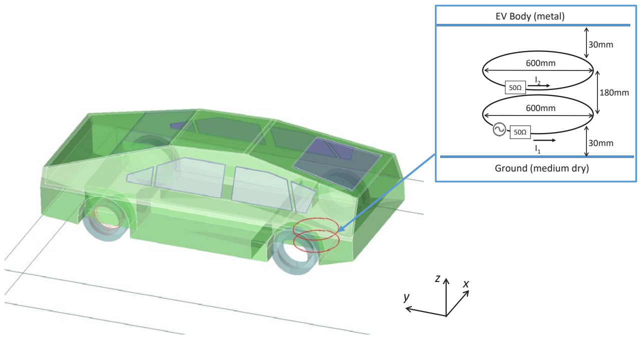


Fig. 2 EV-WPT system to be studied.

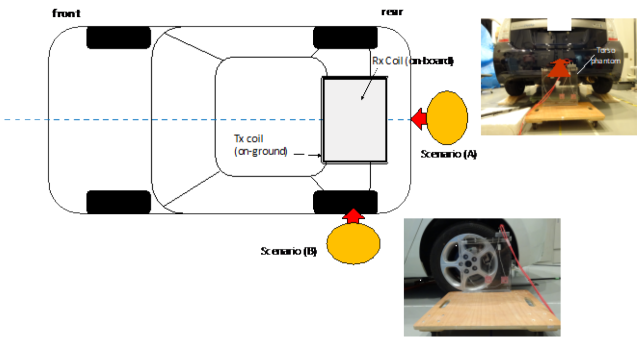


Fig.3 Definition of the position of the torso phantom relative to the EV-WPT. Scenario (A): phantom behind the EV; Scenario (B): phantom near the Rx coil.

on implantable devices. The WPT system includes single-loop transmission (Tx) and reception (Rx) coils positioned between the EV chassis and the ground plane, with a coil-to-coil distance of 180 mm, as shown in Fig. 2. The coils are designed to resonate at 85 kHz, a frequency commonly used in EV WPT systems. To replicate realistic environmental conditions, the ground was modeled as medium dry soil.

For the EMI assessment, the EV-WPT system was combined with the human torso phantom, as shown in Fig. 3, to measure interference voltage under two different exposure scenarios. These scenarios are based on real-world EMI testing conditions reported in [11,12] and represent typical operational environments. In both scenarios, the torso phantom was positioned directly adjacent to the EV body, with a separation distance of 0 mm, replicating close-proximity exposure conditions.

In this study, a 1 A current was applied to both the Tx and Rx coils to simulate typical WPT system operating conditions. The interference voltage was then evaluated by measuring the potential difference across a 1 MΩ resistor connected to the pacemaker terminals inside the phantom. This setup enabled accurate simulation of EMI effects on the pacemaker, providing insights into potential interference levels induced by the WPT system under realistic conditions.

By using the finite element method (FEM), both magnetic and electric field components were considered in the simulation, allowing for a comprehensive assessment of EMI effects originating from both types of fields.

3. RESULTS AND DISCUSSION

Table 2 shows the calculated interference voltages at the pacemaker terminals for both scenarios (A) and (B). Scenario (A) corresponds to the phantom placed behind the EV, while scenario (B) represents the phantom positioned near the Rx coil. The interference voltage values are normalized to 0 dB when the EV body is omitted, and the distance between the phantom and the Rx coil is set to 300 mm. The input power to the coils was kept constant across all scenarios.

Table 2 Calculated interference voltage

Configuration	Distance from the Rx-coil	Relative induced voltage
Without EV body (only Tx and Rx coils on the ground)	300 mm	0 dB
Scenario (A)	670 mm	-15 dB
Scenario (B)	600 mm	-23 dB

The results show that the induced voltage in scenario (A) is more than twice that of scenario (B), despite identical input power, highlighting how variations in magnetic field distribution can significantly influence induced voltages. These field variations, caused by factors such as coil alignment and environmental conditions, play a critical role in determining the degree of interference experienced by the pacemaker.

Furthermore, by calculating the electric and magnetic fields around the WPT coils and within the human phantom using FEM analysis, it becomes possible to accurately estimate the interference signals generated in the internal circuit of the pacemaker. The FEM approach enables detailed modeling of electromagnetic interactions within complex geometries, such as the human body, providing insights into how induced electric and magnetic fields propagate and interact with implantable medical devices. This methodology improves the accuracy of interference predictions by ensuring that subtle variations in field distribution and intensity are fully accounted for in the EMI assessment.

Supported by in-vitro EMI measurements with an actual pacemaker, this evaluation method demonstrates strong potential for accurately predicting EMI risk zones. These findings suggest the possibility of proactively identifying and mitigating EMI risk areas around EV-WPT systems, thereby improving safety for individuals with implantable medical devices in future applications.

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