Compliance Assessment of Human Exposure from Wireless Electric Vehicle Charging (WEVC) System

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Contents

1 ABSTRACT .......................................................................................................................... 5

2 INTRODUCTION .................................................................................................................. 5
   2.1 Block Diagram of WEVC System ................................................................................. 6
   2.2 Coupling Mechanism of EM fields with Human Body .................................................. 6
   2.3 RF EXPOSURE LIMITS ............................................................................................... 6
   2.4 RF EXPOSURE ASSESSMENT APPROACH ................................................................. 8
      2.4.1 Numerical Electromagnetics .................................................................................. 8
      2.4.2 Typical Exposure Cases ....................................................................................... 9
      2.4.3 Homogeneous Body and Limb Models (Dimensions and Dielectric Properties) .... 10
      2.4.4 Effect of Body Loops on Exposure ..................................................................... 13
      2.4.5 Validation .......................................................................................................... 13

3 CASE STUDY ...................................................................................................................... 14
   3.1 DEMONSTRATING COMPLIANCE USING NUMERICAL SIMULATIONS ................. 14

4 CONCLUSIONS .................................................................................................................. 20
Figures

Figure 1. Block diagram of a WEVC system. ............................................................... 6
Figure 2. Reference levels overestimate exposure as they are derived based on the assumption that incident fields have uniform distribution with intensity equal to the peak field strength. .......... 8
Figure 3. Anatomical models of the Virtual Family [6] ........................................................................ 9
Figure 4. A driver and a bystander are shown in typical usage positions relative to the WEVC system .................................................................................................................. 10
Figure 5. Homogeneous phantoms used to represent the human body for compliance assessment: body phantom, arm phantom and leg phantom. ........................................................................ 11
Figure 6. Enhancement factors between anatomical models and homogeneous body phantom were determined for: (A) coronal orientation on top of the transmitter coil representing humans lying on the WEVC system without the electric vehicle, and (B) sagittal orientation representing bystander lying in sideways posture next to the electric vehicle. ........................................ 12
Figure 7. Enhancement factors for the 99th percentile induced electric field (E) and the peak induced current density (J) for a total of 22 simulation cases studied for the orientations shown in Figure 6.......................................................................................................................... 13
Figure 8. Magnetic-field distribution in free-space around a simulated WEVC system. ...................... 14
Figure 9. Offset labeling for various alignments between transmitter and receiver coils. ....................... 15
Figure 10. Influence of alignment offset between transmitter and receiver coils on emitted magnetic fields around a 3.3kW prototype WEVC system. ................................................. 16
Figure 11. Simulated and measured magnetic-field for a prototype WEVC system. ................................. 17
Figure 12. Various orientations of body phantom for bystander exposure assessment. ............................ 18
Figure 13. Induced electric-field distribution in the body phantom for the worst-case bystander orientation. .......................................................................................................................... 18

Tables

Table 1. RF exposure limits for general population for the frequency range from 1 Hz to 10 MHz ........ 7
1 ABSTRACT

As with any wireless system that emits electric-fields or magnetic-fields or both, it is necessary to study the exposure in humans who are in close proximity of such systems. Currents and electric fields are induced inside a human body when exposed to electromagnetic fields. International bodies like IEEE and ICNIRP provide guidelines that define limits on the induced fields based on known biological effects. In this paper, we describe these limits and show an approach using a combination of numerical simulations and experimental validation to perform an assessment of the human exposure from wireless electric vehicle charging systems.

2 INTRODUCTION

Growing electric vehicles share in the market due to obvious advantages over conventional gas-powered vehicles has led to the advancement of charging the batteries in the electric vehicles wirelessly. The wireless charging-enabled electric vehicle when parked over a Wireless Electric Vehicle Charging (WEVC) system located on the floor, WEVC system detects the electric vehicle and starts charging. Thus, the electric vehicle will charge and be ready for operation without the need to plug the electric vehicle in an electrical power outlet.

Wirelessly charging consumer electronics has become popular in recent years finding applications in toothbrushes, cell phones, laptops/tablets, audio/video units, medical implants like pacemakers, etc. Demonstrating compliance with the electric and magnetic field emissions as well as with the induced fields inside humans who are in close proximity is a must prior to releasing the product in the market. Since WEVC systems typically operate at low frequencies (~100 kHz), where there are no standardized procedures to demonstrate compliance with the induced fields inside humans, new approaches have to be developed. In this paper, we propose an approach employing both numerical electromagnetic simulations as well as field measurements (for validation) for the assessment of the induced fields from WEVC systems [1].
2.1 Block Diagram of WEVC System

A WEVC system transfers electrical energy from the power grid to an electrical load (battery) inside the electric vehicle via electric and or magnetic fields or waves between a transmitter coil and a receiver coil as shown in Figure 1.

![Block diagram of a WEVC system.](image)

2.2 Coupling Mechanism of EM fields with Human Body

Electric fields emanating from WEVC systems are highly localized around the transmitter and receiver coils. In this application, magnetic field emissions around the WEVC system are dominant since these systems are operated with coils carrying high currents. Therefore, electromotive force (EMF) proportional to the rate of change in coupled magnetic flux (Faraday's law of induction) is induced inside humans present near the WEVC system. This EMF results in induced electric fields (and currents) inside the human body, which vary depending on the conductivity of human tissue as well as the inhomogeneity of human tissue structure.

2.3 RF EXPOSURE LIMITS

International bodies like the International Commission on Non-Ionizing Radiation Protection (ICNIRP) and the Institute of Electrical and Electronics Engineers (IEEE) provide guidelines to limit the human exposure from time-varying electric, magnetic and electromagnetic fields [2], [3], [4]. Restrictions on RF exposure that are based directly on established health effects are termed as “Basic Restrictions”. ICNIRP provides basic restrictions: (a) on induced current density (ICNIRP 1998) or induced electric field (ICNIRP 2010) to prevent nerve stimulation for frequencies < 10 MHz, (b) on specific absorption rate (SAR) to prevent tissue heating for frequencies between 100kHz and 10 GHz, and (c) on power density to prevent heating in tissue at or near the body surface for above 10 GHz.
RF Exposure Limits for General Population (1 Hz to 10 MHz)

<table>
<thead>
<tr>
<th>Standard</th>
<th>1 Hz – 10 MHz</th>
<th>100 kHz – 10 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Induced $E$ (V/m)</td>
<td>Induced $J$ (mA/m$^2$)</td>
</tr>
<tr>
<td>ICNIRP 1998</td>
<td>--</td>
<td>f/500 (f in Hz)</td>
</tr>
<tr>
<td>ICNIRP 2010</td>
<td>1.35 x 10^{-4}f</td>
<td>--</td>
</tr>
<tr>
<td>FCC</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

Table 1. RF exposure limits for general population for the frequency range from 1 Hz to 10 MHz

Since it is difficult to assess induced fields inside the human body, ICNIRP provides “Reference Levels” in terms of incident electric and magnetic fields for practical exposure assessment in order to determine whether the basic restrictions are likely to be exceeded. These reference levels were derived from the basic restrictions under the worst case coupling condition of a homogenous human body model exposed to uniform incident fields. Similar to the reference levels, IEEE provides Maximum Permissible Exposure (MPE) levels in terms of external electric and magnetic fields, contact currents and power density, for convenience in exposure assessment to ensure that basic restrictions are met.

It should be noted that the reference levels do not specifically address localized exposures; they were determined to represent the incident field levels that are spatially averaged over the entire body of an exposed individual. Moreover, they were determined using homogeneous models and therefore would not provide an accurate estimate for highly inhomogeneous anatomical human models. Hence, the reference levels do not apply well for high-gradient fields that occur in the vicinity of WEVC systems. Even if the reference levels are exceeded, it does not necessarily follow that the basic restrictions have been exceeded, but a more detailed analysis is necessary to assess the compliance with the basic restrictions.

Due to the presence of high gradient fields in the vicinity of WEVC systems, the reference levels are typically exceeded at the peak location of the fields. Applying the reference levels for compliance would then imply that the field strength at all locations is equal to the peak value (see Figure 2), which will obviously result in an overly conservative assessment. Therefore, a more comprehensive assessment of basic restrictions is needed for the WEVC application.
INTRODUCTION

Figure 2. Reference levels overestimate exposure as they are derived based on the assumption that incident fields have uniform distribution with intensity equal to the peak field strength.

2.4 RF EXPOSURE ASSESSMENT APPROACH

2.4.1 Numerical Electromagnetics

Method of Moments (MoM), Finite-Element Method (FEM), Finite Difference Time Difference (FDTD) and Integral Equation (IE) methods are the most popular methods employed for numerical electromagnetic simulations. Each method has its own advantages and disadvantages, and is not suitable for all electromagnetic problems. Therefore, over the years, many variants of FDTD and FEM methods were developed in the literature by trading off some of the advantages to make them more suitable for specific applications.

FDTD method is particularly suitable for running electromagnetic simulations involving complex inhomogeneous structures like human anatomical models [5]. Virtual Family models (see Figure 3) containing a 34-year-old male model, a 26-year-old female model, a 11-year-old girl model and a 6-year-old boy model, are suitable for such evaluations as they are available at high resolutions (1mm for body and 0.5mm for head regions) with more than 80 different tissues and organs of the human body [6]. However, at low frequencies (~100 kHz), voxels of discretized human body model (within few mm) are extremely small compared to the wavelength, which in turn determines the minimum time step based on the Courant-Frederick-Lewy stability criteria. Therefore, FDTD simulations at low frequencies require thousands (ratio of time period to minimum time step) of iterations resulting in extremely long times for the simulations to converge [7].
FEM method on the other hand has a limitation in running complex inhomogeneous structures like anatomical human models. However, since it is a frequency domain-based simulation solver, FEM method is suitable for low frequency exposure assessment albeit using homogeneous phantom models or simplified human models containing few layers such as skin, fat, bone and muscle.

Therefore, it is important to employ a hybrid approach to assess the induced fields inside humans from WEVC systems. A work around for the low frequency limitation in FDTD is to employ frequency scaling [8], [9], [10]. At low frequencies, frequency scaling can be applied if the quasi-static condition \((\omega \varepsilon_0 \varepsilon_r << \sigma)\) is satisfied for the dielectric properties of all human tissues [11]. Alternatively, quasi-static solvers based on Finite Elements can also be used. These methods can be used to develop homogenous models that represent the worst-case exposure in the trunk and the limbs of a human body. Consequently, FEM simulations can be easily performed with such homogeneous models placed near WEVC systems. Minimum separation distance between a WEVC system and the homogeneous models where compliance with the induced field limits is achieved is referred to as the “compliance distance”. If humans in typical usage conditions stay away from the WEVC system by more than this distance, then the WEVC system is deemed to be compliant with the RF exposure limits.

2.4.2 Typical Exposure Cases

The hybrid approaches described above can be used to demonstrate RF exposure assessment in typical usage scenarios with respect to applicable limits. For example, determining induced current density \((J)\) in the Central Nervous System (CNS) and/or induced electric field \((E)\) in bystanders, driver and passenger(s) while they are in typical usage position(s) would be the first step in demonstrating compliance (see Figure 4).
Since humans can be in many different postures inside the electric vehicle as well as outside, it becomes impractical to show compliance in all possible postures (sitting, standing, lying down, etc.) and anatomical structures (male vs. female, adult vs. child, etc.). Therefore, it is important to develop homogeneous tissue phantoms that represent the worst-case exposure in humans for practical assessment of compliance of WEVC systems with respect to the RF exposure limits.

2.4.3 Homogeneous Body and Limb Models (Dimensions and Dielectric Properties)

Comprehensive RF exposure assessment of the induced fields in humans present next to WEVC systems will require simulating different human models, various postures and at many separation distances. This will lead to time-consuming approach even when applying frequency scaling in FDTD or performing quasi-static simulations. Alternatively, we propose to: (a) develop homogeneous body and limb models that represent bulk coupling in anatomical models, and (b) determine worst-case enhancement factors to account for the conservativeness of
homogeneous tissue phantoms relative to the localized exposures in inhomogeneous anatomical models.

**Body phantom:** ITIS foundation has recently developed a homogeneous body phantom to represent the 95\textsuperscript{th} percentile SAR absorption from base station antennas in the human population using the statistical data of weight, height and body-mass index of the human population [12], [13]. It was developed for the exposure assessment in the near field of base stations operating between 300 MHz and 5 GHz. This body phantom has dimensions of 1540 mm in height, 340 mm in width and 90 mm in depth. At low frequencies, it represents bulk coupling of the electromagnetic exposure observed in the trunk part of the human body. However, this body phantom doesn’t represent the electromagnetic exposure in the limbs of the human body.

**Limb phantoms:** Dimensions of limb phantoms were chosen to represent wrists and thighs of the 95\textsuperscript{th} percentile of the human population [14]. The arm phantom is 810mm in length having square cross-section of 48mm width. Similarly, the leg phantom is 910mm in length having square cross-section of 170mm width.

![Figure 5. Homogeneous phantoms used to represent the human body for compliance assessment: body phantom, arm phantom and leg phantom.](image)

**Dielectric Properties:** The dielectric properties of the homogeneous phantom should be chosen such that (a) they are representative of human tissue and (b) they do not underestimate the exposure levels in humans. Traditionally, muscle tissue has been used to represent the body [15]. Here, homogenous phantom with muscle tissue properties having adequate cross-section simulates the worst-case bulk coupling of electromagnetic exposure for the human body. Similarly, SAM phantom with brain (grey matter) tissue properties can be used for assessing the induced current density in the Central Nervous System (CNS) as required by ICNIRP 1998 [16].

**Worst-case enhancement factors:** When performing an exposure assessment using the homogeneous phantoms, it is necessary to ensure that the exposure in the homogeneous phantoms is conservative relative to the anatomical models. Therefore, exposure in the homogenous phantoms should be verified for conservativeness against different anatomical...
models structures, various orientations of the anatomical models relative to the source and at different separation distances. For this purpose, worst-case enhancement factors are typically used to scale the exposure determined in homogeneous phantoms [17].

Enhancement factor is defined as the ratio of peak exposure metric (induced J or E) found in inhomogeneous anatomical models to that of the homogeneous phantom. They are determined for numerous cases by performing simulations with various anatomical models at different locations relative to the WEVC system. Simulations were performed on all the anatomical models of the virtual family by placing each of them in coronal orientation (lying posture) on top of the transmitter coil at closer separation distance (see Figure 6A) of 50 mm and also in sagittal orientation (lying sideways) for bystanders (see Figure 6B) at a typical separation distance of 500 mm. Additionally, the anatomical models were moved along the broader dimension of the transmitter coil in order to expose different regions of the human body resulting in a total of 22 simulations for all four anatomical models of the virtual family. Standing postures of the virtual family were not simulated for assessing the worst-case enhancement factor as they would result in lower exposure (lower coupled flux) when compared with lying postures shown in Figure 6.

![Figure 6](image_url)

**Figure 6.** Enhancement factors between anatomical models and homogeneous body phantom were determined for: (A) coronal orientation on top of the transmitter coil representing humans lying on the WEVC system without the electric vehicle, and (B) sagittal orientation representing bystander lying in sideways posture next to the electric vehicle.

The homogeneous body phantom with muscle tissue was also simulated in same locations and orientations relative to the transmitter coil as the anatomical models for determining the enhancement factors for 99th percentile of induced electric field (as required by ICNIRP 2010), and peak induced current density (J). Subsequently, the cumulative distribution of enhancement factors was plotted in order to determine the 95th percentile value and also to check if there is a
need to scale exposure values in the homogeneous body phantom for obtaining a conservative exposure assessment. As can be seen from Figure 7, the 99th percentile value of the induced electric field and the induced current density in the anatomical models is conservative (ratio < 1) relative to the peak electric field and the peak current density induced in the homogeneous body phantom, respectively.

![Enhancement Factors (anatomical/homogeneous)](image)

**Figure 7.** Enhancement factors for the 99th percentile induced electric field (E) and the peak induced current density (J) for a total of 22 simulation cases studied for the orientations shown in Figure 6

### 2.4.4 Effect of Body Loops on Exposure

In addition to determining the exposure for the worst-case posture of human anatomical models and at the worst-case orientation relative to the WEVC system, we have observed further enhancement in exposure when a loop is formed with parts of the body, e.g., both hands touch each other or hands touch the body [18]. Body loops couple additional magnetic flux cutting through the airspace enclosed by the loop, and would result in enhanced induced currents/fields that concentrate in narrow cross-section regions of the loop like fingertips [18]. The additional enhancement resulting from such corner cases could under-estimate exposure assessment using the homogeneous phantoms. In this paper, such corner cases showing additional enhancements in the exposure from body loops are not demonstrated.

### 2.4.5 Validation

In order to validate the simulation results and in particular, to verify if the numerical model of the WEVC system used in the simulations is an accurate representation of the physical device, simulated free-space magnetic fields emitted by the WEVC system are compared with the measured fields. Additionally, uncertainty budget analysis should be performed for both simulations and measurements to determine the overall combined uncertainty. If the deviation between the simulated and the measured free-space magnetic fields is within the combined uncertainty, then the simulation model chosen is determined to be a good representation of the
WEVC system. Otherwise, the accuracy of the WEVC simulation model needs to be improved before performing the RF exposure assessment using the numerical simulations.

3 CASE STUDY

3.1 DEMONSTRATING COMPLIANCE USING NUMERICAL SIMULATIONS

The following are the steps we performed to demonstrate compliance for a WEVC system:

a) *Modeling WEVC system:* Wireless power transfer system was modeled using the geometry of the coil structures, operating frequency and maximum operating currents in both the transmitter and the receiver coils along with their relative phase information.

b) *Determining worst-case for incident fields:* Since there are many variables involved that impact the fields emitted from the WEVC system like car dimensions, worst-case ground conditions, separation and alignment offset between transmitter and receiver coils, and magnitudes as well as the relative phase difference between the transmitter coil current and the receiver coil current, etc., their influences can be numerically simulated to determine the worst-case emitted magnetic fields. Here, it is presumed that the emitted electric fields are extremely localized around the coils and are therefore less of a concern in terms of RF exposure.
- Figure 9 and Figure 10 below show the influence of the offset in the alignment of transmitter and receiver coils on the magnetic fields for a 3.3kW prototype WEVC system.

<table>
<thead>
<tr>
<th>Alignment (0, 0)</th>
<th>X_Offset (x, 0)</th>
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<td><img src="image" alt="X_Offset Diagram" /></td>
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<table>
<thead>
<tr>
<th>Y_Offset (0, y)</th>
<th>X_Offset, Y_Offset (x, y)</th>
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<tr>
<td><img src="image" alt="Y_Offset Diagram" /></td>
<td><img src="image" alt="X_Offset, Y_Offset Diagram" /></td>
</tr>
</tbody>
</table>

Figure 9. Offset labeling for various alignments between transmitter and receiver coils.
Figure 10. Influence of alignment offset between transmitter and receiver coils on emitted magnetic fields around a 3.3kW prototype WEVC system.

c) **Validation:** As mentioned above, magnetic field values measured in the presence of an electric vehicle were compared with the simulated fields to see if the deviation is less than the combined expanded uncertainty of measurements and simulations. This is necessary for verifying the accuracy of the WEVC simulation model prior to performing RF exposure assessment. Figure 11 shows an example of good correlation between measured and simulated magnetic field emanating from a prototype WEVC system.
### Table 1

<table>
<thead>
<tr>
<th></th>
<th>P3</th>
<th>P4</th>
<th>P5</th>
<th>Worst Pt</th>
<th>P6</th>
<th>P7</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Measured B (uT) at evenly spaced points</strong></td>
<td>1.12</td>
<td>2.32</td>
<td>4.76</td>
<td>missed</td>
<td>2.02</td>
<td>0.70</td>
</tr>
<tr>
<td><strong>Measured B (uT) at the worst location</strong></td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>5.62</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td><strong>Simulated B (uT)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>At rated electrical parameters</td>
<td>1.34</td>
<td>2.62</td>
<td>5.62</td>
<td>6.91</td>
<td>2.60</td>
<td>0.91</td>
</tr>
<tr>
<td>Under the condition of ± 10% operation range</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>4.61 ~ 7.38</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

**Figure 11.** Simulated and measured magnetic-field for a prototype WEVC system.

d) **Uncertainty Analysis:** Uncertainty assessment for both measurements and numerical simulations were performed in order to validate the accuracy of WEVC model representation in the simulations. The total uncertainty is calculated by performing the root-mean-square of various uncertainty sources, assuming that they are independent or have limited interdependencies. Uncertainty assessment for free-space magnetic field measurements involves the determination of uncertainties from probe calibration, probe isotropy, linearity, RF ambient noise, separation distance, source power drift, etc. Numerical simulation uncertainty assessment involves the determination of uncertainties from simulation parameters, convergence, tissue parameters, source modeling, etc.[19]

e) **Compliance Distance Estimate:** RF exposure was evaluated for various orientations and separation distances using the homogeneous body and limb phantoms in order to determine the minimum separation distance(s) required for compliance with the limits.
For WEVC application, if the compliance distance is less than the dimensions of the electric vehicle, then the WEVC system is deemed to be compliant as bystanders adjacent to the electric vehicle will be inherently at a distance larger than compliance distance.

- Figure 12 shows an example of performing the assessment with the homogeneous body phantom. The body phantom is positioned in the hot spot identified for worst-case magnetic fields (section 3.1b) and then the exposure is evaluated for various orientations (standing, lying down and lying down sideways).

![Figure 12. Various orientations of body phantom for bystander exposure assessment.](image)

- We have observed highest exposures (internal electric field and induced current density) when positioning the phantom close to the edge of the electric vehicle and in the orientation shown in Figure 13. (lying down sideways).

![Figure 13. Induced electric-field distribution in the body phantom for the worst-case bystander orientation.](image)
- Enhancement factor (see Figure 7) was also taken into account to determine the worst-case exposure for a bystander, which was less than ICNIRP’s basic restrictions.
- In this particular example, the minimum separation distance for compliance was less than the half-width of the electric vehicle. Therefore, the system evaluated is in compliance with ICNIRP basic restrictions for bystanders.
Electromagnetic exposure in humans who are in close proximity of WEVC systems requires new approaches for estimation due to the lack of standardized procedures for RF exposure assessment at low frequencies (<10 MHz). In this paper, we have described the exposure limits provided by international bodies like ICNIRP, and proposed an approach to assess induced fields inside humans using a combination of numerical simulations and experimental validation for demonstrating compliance of WEVC systems.

The following steps are proposed for demonstrating WEVC system’s compliance with RF exposure requirements:

- Perform numerical electromagnetic simulation to simulate the free-space field distribution around the WEVC system.
- Experimentally validate the free-space magnetic fields in order to verify the accuracy of the WEVC simulation model.
- Perform numerical simulations for various usage scenarios and separation distances using simplified homogeneous phantoms that represent bulk coupling of the electromagnetic exposure in anatomical models.
- Scale the exposure results using worst-case enhancement factors in order to obtain conservative exposure assessment in inhomogeneous anatomical human models.
- Determine minimum separation distance of humans with respect to the WEVC system for compliance.

Compliance with the exposure limits is guaranteed if humans in close proximity of the WEVC system are farther than this minimum separation distance in all usage scenarios. This proposed approach was demonstrated using a case study for a prototype WEVC system.
(a) REFERENCES


[16] ICNIRP. Response to questions and comments on guidelines for limiting exposure to time-varying electric, magnetic and electromagnetic fields (up to 300 GHz), Health Physics, 75(4):438-439, 1998.
