Induced Current Calculation in Detailed 3D Adult and Child Model for the WPT Frequency Range

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***Abstract*—In this work, induced current density in the high-resolution 3D adult and child model, which is the basic restriction of the EMF (Electromagnetic Field) protection guideline, is calculated. The models are exposed to magnetic fields between 100 kHz-10 MHz, which is also the frequency range of the resonant WPT (Wireless Power Transfer) systems. For this frequency range, it is difficult to apply conventional FDTD (Finite-Difference Time-Domain) method for bioelectric field computation. Thus, the induced current distribution is calculated using quasi-static FDTD method to reduce the number of time-steps. Using the calculation results, the feasibility of the magnetic field reference levels in the ICNIRP (International Commission on Non-Ionizing Radiation Protection) guidelines are analyzed.**

***Index Terms*—Bioelectric phenomena, biomagnetics, dosimetry, finite difference methods.**

I. Introduction

As the technologies such as middle-range resonant WPT (Wireless Power Transfer) advance that utilizes low-frequency magnetic fields, the importance of safety for such low-frequency magnetic fields is growing. The research on the effect of electromagnetic field on the human body has been mainly focused on the a few GHz range of mobile phones, or 50-60 Hz range of electric power systems. On the other hand, there has been relatively few works on the dosimetry of magnetic fields in the 100 kHz-10 MHz frequency range used in the resonant wireless power transfer systems. Since there is a difference in the limiting values of magnetic fields between widely used ICNIRP guideline and IEEE C95.1 standard, there can be possible confusion when establishing EMF (Electromagnetic Field) standard on the wireless power transfer device in the future. Thus, it is necessary to study magnetic field dosimetry for various 3D human models in 100 kHz-10 MHz. For this frequency range, it is difficult to apply conventional FDTD (Finite-Difference Time-Domain) method for bioelectric field computation, because the number of time-steps increases exponentially to satisfy the Courant stability condition. Thus, quasi-static FDTD method is used in this paper to reduce the number of time-steps considerably. Using the calculation results, the feasibility of the magnetic field reference levels in the ICNIRP (International Commission on Non-Ionizing Radiation Protection) guidelines are analyzed.

II. Quasi-Static FDTD Method

In this chapter, quasi-static FDTD method that is used for induced current calculation in the human models is reviewed [1]. Since the size of time-step is determined by Courant stability condition in the conventional FDTD method, the number of time-steps to simulate several periods increases prohibitively in the low-frequency range when the voxel size is very small, which is often the case in the detailed 3D human models. Using the quasi-static FDTD method, the number of time-steps can be decreased considerably while maintaining the simplicity of FDTD scheme [1].

For a quasi-static system, the size of the analysis domain should be smaller than 10% of the wavelength, and the following condition should be satisfied,

$$|\sigma + j\omega\varepsilon| \gg \omega\varepsilon_0 \quad (1)$$

where σ is tissue conductivity, ε is tissue permittivity, $\omega = 2\pi f$ is angular frequency, and ε_0 is permittivity of free space. Under these conditions, the electromagnetic field outside the biological tissue (or the field in the free space) has the same phase as the incident field, while the field inside the biological tissue has the same phase as the time derivative of the incident field [1]. Thus, if a ramp function is used as an incident field, the fields outside the tissue change linearly, while the fields inside the tissue remain constant. Hence, if the starting waveform of time-harmonic electromagnetic field with very long period is approximated by a ramp function, the steady-state electric and magnetic field inside the biological tissue can be calculated by storing fields at two time steps after the steady-state has been reached. Since the steady-state of the quasi-static system can be reached in much shorter time than one full period, the electromagnetic field distribution in the analysis domain can be determined in a very small time portion of one period. To suppress the harmonic components of the incident field, the modified ramp function is used as follows,

$$E_{inc} = \begin{cases} 0, & -\infty < t \le t_0 \\ \frac{1}{2}\left(t - \frac{\tau}{\pi}\sin\frac{\pi t}{\tau}\right), & t_0 < t \le \tau \\ t - \tau/2 & t > \tau \end{cases} \quad (2)$$

where τ is about $100\Delta t$ in general cases.

III. Induced Current Calculation in Human Models

In this chapter, quasi-static FDTD method is applied to induced current calculation in detailed 3D human adult and child models, and the results are analyzed. For this work, male adult and child models in the virtual family voxel models were used (Fig. 1) [2]. The "Duke" model (174 cm) is from MRI data of 34-year-old male, and the "Thelonious" model (107 cm) is from those of 6-year-old male child. Both models have more than 70 distinct biological tissues, and for electric parameters of tissues, the values from C. Gabriel were used [3].

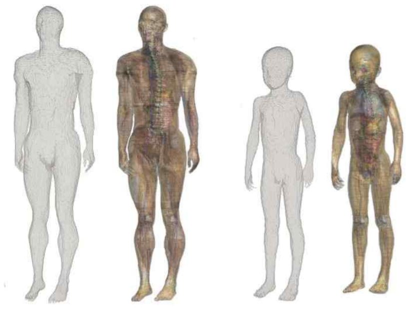


Fig. 1. Detailed 3D human models (34-year-old and 6-year-old) and their internal structure.

The voxel size of the models can be adjusted as needed, and 5*5*5 mm models were used in this work. The models are exposed to 100 kHz-10 MHz magnetic field, which is the same frequency range used in the resonant wireless power devices. To account for maximum exposure situation, the direction of the magnetic fields are set to be perpendicular to the maximum cross-section of human models (-*y* direction in Fig. 2 and 3). Also, for reference, the same magnetic flux density of 30.7 μT , which is the occupational exposure limit for low-frequency in 1998 ICNIRP guideline, was used in all cases. Since the grounding condition of both feet can have some effect on the induced current distribution, 2 grounding conditions are considered; when both feet are in contact with PEC (Perfect Electric Conductor) ground plane, and when there is no PEC ground plane for both feet.

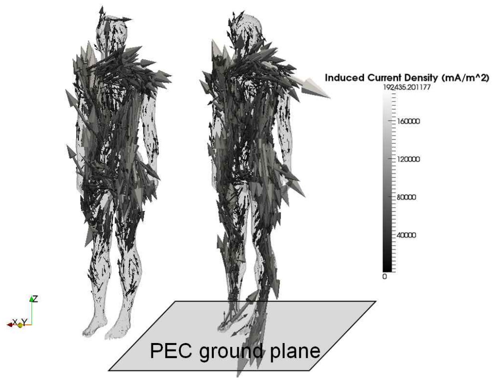


Fig. 2. Induced current density distribution in 34-year-old human model for 2 different grounding conditions (10 MHz magnetic field exposure).

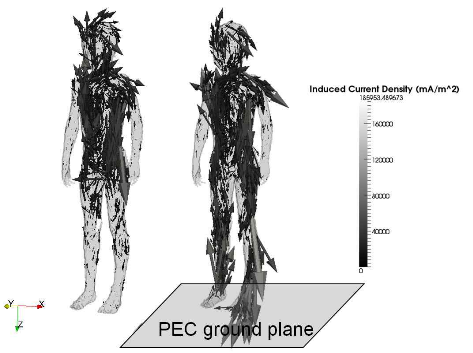
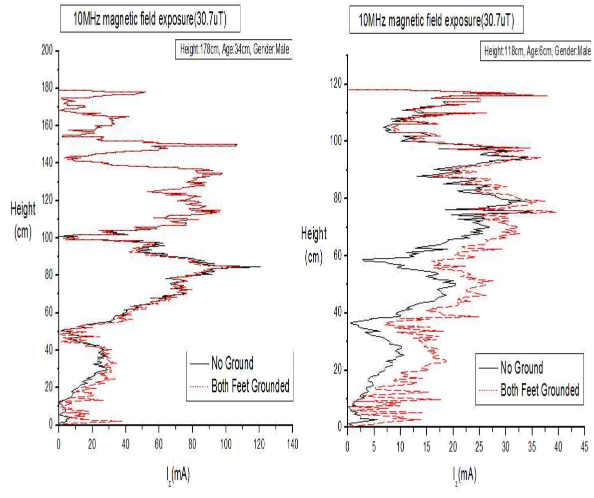


Fig. 3. Induced current density distribution in 6-year-old human model for 2 different grounding conditions (10 MHz magnetic field exposure).

From Fig. 2 and 3, it can be clearly seen that the induced current near the ankles and the legs is increased when both feet are grounded. Finally, Fig. 5 shows maximum value of induced current in human models between 1-10 MHz. The maximum induced current increases linearly as frequency increases, and maximum current at 10 MHz is about 4 times larger in the adult model compared to that of child model. Based on simulation results, the detailed analysis of the reference levels in EMF guidelines will be given in the extended paper.



(a) (b)

Fig. 4. Distribution of *z*-component of induced current (I_z) along *z*-axis in human models for 2 different grounding conditions (10 MHz magnetic field exposure). (a) 34-year-old model. (b) 6-year-old model.

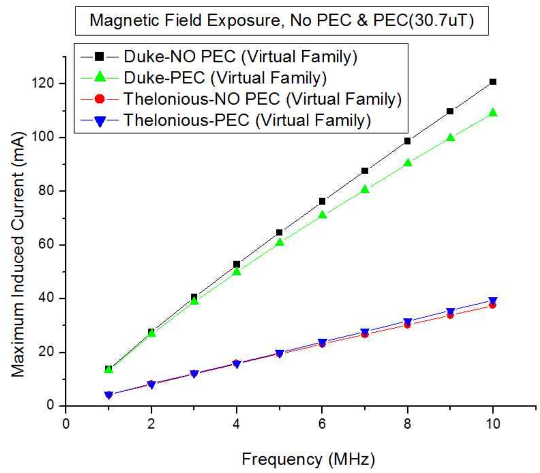


Fig. 5. Maximum induced current for adult and child human models for frequency range between 1 MHz and 10 MHz.

References

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