IEICE TRANS. ELECTRON., VOL.E93–C, NO.1 JANUARY 2010

PAPER Special Section on Recent Progress in Electromagnetic Theory and Its Application

Quasi-Static FDTD Method for Dosimetry in Human due to Contact Current

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SUMMARY The present study proposes a quasi-static finite-difference time-domain (FDTD) method for dosimetry in humans due to contact current at low frequencies (~10 kHz). Our attention focused on wave sources which can reduce computational time. The computational time was found to be reduced using a voltage source of a step function with smooth start. The computational time required for the proposed method was smaller than a quasi-static FDTD method proposed in a previous study. Comparison between our computational results and those in a previous study suggested the effectiveness of our proposal. The difference in *in-situ* electric field due to different human models was a factor of 2 or so.

key words: *quasi-static finite-difference time-domain method, contact current, dosimetry*

1. Introduction

There has been increasing public concern about adverse health effect due to electromagnetic fields. Thus, international standardization bodies have regulated safety guidelines/standards for human protection against electromagnetic field [1], [2]. According to these guidelines/standards, induced current density [1] or *in-situ* electric field [2] is used as a metric for fields lower than 10 MHz [1]. Until recently, much attention has been paid to human exposure to electric and magnetic fields in free space and/or on the ground in order to clarify the relationship between the basic restriction [1], [2] and the reference level [1]/maximum permissible exposures [2]. Note that restrictions on exposure to time-varying electromagnetic fields that are based directly on established health effects are termed "basic restrictions," while the "reference levels" are defined as external field strength for practical exposure assessment purposes to determine whether the basic restrictions are likely to be exceeded [1]. Namely, the main purpose of the previous studies was to relate the *in-situ* field and corresponding external field for 'direct coupling' between human and fields.

In the safety guidelines [1], 'indirect coupling' between fields and humans are defined. One of the exposure scenarios for indirect coupling is 'contact currents' that happens when the human body comes into contact with an object at a different electric potential. A reference level for contact current has been prescribed in terms of injection current. However, only a limited number of studies have investigated human dosimetry due to contact current [3], [4]. These studies have pointed out that the basic restriction is not satisfied for exposure at the reference level. In addition, idealized or simplified scenarios have been considered; human is standing in the free space, and then electrodes have been attached to some body parts. The main reason for this limitation is that a computational method in these studies was the scalar-potential finite-difference method [5], which cannot take into account complicated sources and environmental structures.

The Finite-Difference Time-Domain (FDTD) method [6], [7] is one of the well-known computational methods, due to its capability for handling realistic structures. In the FDTD method, however, computational time becomes extremely large when considering problems at low frequencies. This is because, in the FDTD method, a few time periods are required for getting steady state when considering lossy medium. Then, the time iteration needed for a specific period becomes large with the decrease of the frequency. In order to overcome this limitation, a quasi-static FDTD method has been proposed for biological bodies [8]–[10]. Quasi-static FDTD methods are applicable when the displacement current can be neglected as compared with the conduction current. For uniform electric/magnetic field exposures at 50/60 Hz, the effectiveness of the quasi-static approximations has been demonstrated by two research groups. In one scheme [8], the computation has been conducted in the following manners: i) the electrical constant of tissue at an interest frequency is used, ii) computation has been conducted at a frequency higher than the target frequency at which the quasi-static approximation is still applicable, and iii) computational results are scaled back by multiplying a ratio of the frequency at which computation has been conducted to the interest frequency. Note that the formula proposed in [8] has been applicable only to the dosimetry in free space. The other scheme [9], [10] has taken advantage of the fact that fields exterior to objects in which displacement current can be neglected have the same phase as the incident field. The interior fields, on the other hand, are first-order fields that are proportional to the time derivative of the incident field. Then, the incident field is chosen as a ramp function. The latter idea cannot be applied to dosimetry due to contact current, since the boundary condition is essentially different.

In the present study, we proposed a quasi-static FDTD method for dosimetry in humans due to contact current at low frequencies (~10 kHz). For comparison, we used the

Manuscript received April 24, 2009.
Manuscript revised August 12, 2009.

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DOI: 10.1587/transele.E93.C.60

scheme in [8]. The feature of the method proposed in the present study is that a waveform of the source only is modified to apply the quasi-static approximation. Our attention focused on wave sources which can reduce computational time. Then, the effectiveness of the method has been presented with computational results.

2. Computational Model and Methods

2.1 Numeric Human Models

A human body model was constructed from an anatomically-based human body model developed at Brooks Air Force Base [11]. This human model was first homogenized, which is a reasonable simplification for discussing the fundamental characteristics of the proposed method. The resolution of the original model was 1 mm, and thus we rescaled the model so that the height and weight become close to those of Japanese adult male. The resolution of the model is chosen as 5 mm. The height and weight of the rescaled model are 1.70 m and 71 kg. This homogeneous rescaled model is used in Sect. 3.1. In addition, an anatomically based adult male model named TARO is also used to validate our computational results in comparison with previous study [12]. This model has been developed at National Institute of Information and Communications Technology (NICT, Japan). The resolution of the model was 2 mm segmented into 51 anatomical regions. The height and weight of the model is 1.73 m and 65 kg.

2.2 Computational Methods

The FDTD method was used for investigating the induced current density/*in-situ* electric field in the human body. The FDTD formulation for the quasi-static problems is the same as that of a conventional FDTD method for high frequencies [6], [7]. The main difference is attributed to a waveforms given at a source, which is determined by considering the feature of quasi-static electromagnetics. Note that the quasi-static approximation is valid when the displacement current is sufficiently smaller than the conduction current; $\sigma \gg 2\pi f\varepsilon$. Note that σ, ε, and f denote the conductivity and permittivity of tissues and the frequency of the electromagnetic wave. For typical electrical constants of biological tissues, this relationship is well satisfied for $f \simeq$ 10–100 kHz. When the above condition is satisfied, the frequency scaling of the computed results becomes reasonable as in [8].

The side length of the FDTD cell was chosen as 2 or 5 mm, which coincides with the resolutions of the human model. For truncation of the computational region, 12-layered PML (perfect matched layer) was used. The effectiveness of PML for low-frequency application has been investigated in [13]. Note that the rationale for the effectiveness at low frequencies is that the group velocity of low-frequency electromagnetic fields in PML is sufficiently slow so that the reflection from the edge of the computational region cannot come back at practical iterations.

2.3 Electrical Constants of Biological Tissue

In [14], measured electrical constants of tissues have been presented. In low frequencies, uncertainty in electrical constants is relatively large, since the data measured at higher frequencies are extrapolated on the basis of Cole-Cole equation. Reference values of the conductivities of biological tissues at 50/60 Hz were chosen by IEEJ Investigation Committee on Electric Field and Current Induced in a Human Body Exposed to Electromagnetic Fields [15]. In our computation, these values were used. As mentioned in Sect. 2.2, the permittivity influence marginally *in-situ* field in the human body, since the displacement current can be neglected. The permeability of the human tissues is the same as that in free space.

When considering homogeneous human/spheroid models, the electrical constants of 2/3 that of muscle were used. Note that the human body is comprised of high and low water content tissues with the ratio of 2:1. The electrical constants of low-water-content tissues, such as fat and bone, are much smaller than those of high-water-content tissues, such as muscle. Therefore, the electrical constant of 2/3 that of muscle, which is a representative of high water content tissue, is often considered for fundamental discussion. The conductivity for 2/3 of that of muscle is 0.233 S/m at the frequencies of 50/60 Hz.

2.4 Wave Sources

An equivalent voltage source with one cell gap is used to simulate the contact current. Based on [8]–[10], we considered two excitation waveforms. In the scheme (I), a sinusoidal wave has been injected at the one-cell gap. A frequency higher than the target frequency at which quasi-static approximation is still applicable is used, and then the computational results are rescaled by a ratio of the target frequency to the frequency at which computation has been conducted. Note that the electrical constants at the target frequency are used in the computation.

In the other scheme (II), we chose a step function with a smooth start. The rationale for this is that the current is directly injected into the human unlike the case in free space [9], [10]. The voltage source for contact current is given by the following equation:

$$V(t) = \begin{cases} V_0 \dfrac{2}{\tau_0^2} t^2 & 0 < t \le \tau_0/2 \\ V_0 - V_0 \dfrac{2}{\tau_0^2} t^2 & \tau_0/2 < t \le \tau_0 \\ V_0 & t > \tau_0 \end{cases} \quad (1)$$

where V_0 is the RMS value of the voltage for injected current. The computation has been conducted till local field becomes electromagnetically steady state. Steady-state fields

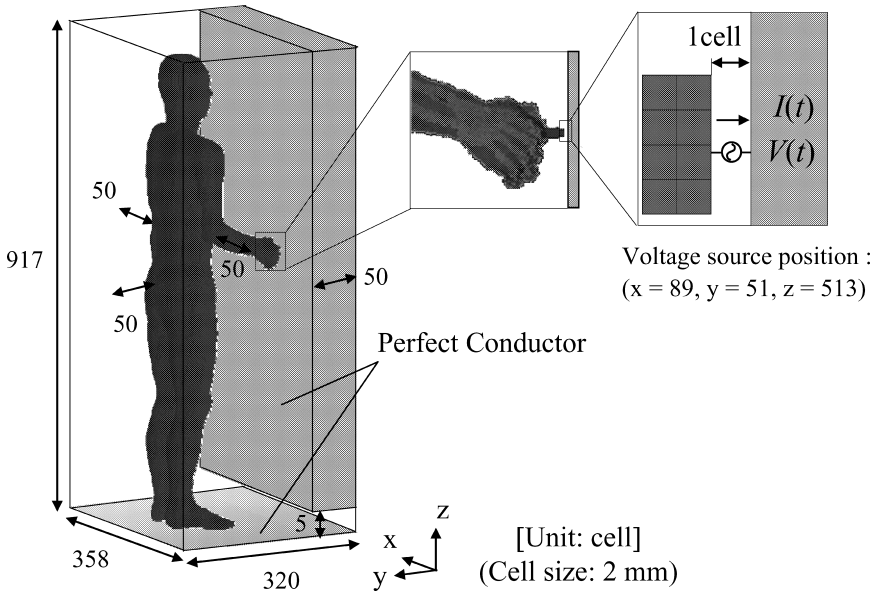

Fig. 1 Exposure scenario for contact current. Grounded human is standing in front of ungrounded conducting object and holding metal piece with right hand.

in biological bodies represent induced fields due to conduction current. The computational error becomes several percents or more without a smooth start ($t < \tau_0$). The main factor for this computational error is high-frequency contamination. When high-frequency contamination happens, time course of local field takes the ripples or oscillation components. Thus, it becomes difficult to evaluate properly the induced field. Even though τ_0 depends on the time step ΔT of the FDTD method, which is determined by the Courant condition, τ_0 should be larger than 200 iterations (200 ΔT [s]) in our computation for the spatial resolution of 5 mm. For the above reason, the function form for $t < \tau_0$ is almost arbitrary if $V(t)$ and its time derivative $V'(t)$ are continuous at $\tau_0/2$ and τ_0.

2.5 Exposure Scenario

Figure 1 shows the schematic scenario of dosimetry in human body due to contact current. Human with hand-held metal piece is standing on the conducting plate. There exists one-cell gap between the hand-held metal piece and the metallic object in front of the human body. The human right arm and hand were bent so as to realize a realistic scenario. The separation between the ground and the conducting object in front of the human was chosen as 5 cells. Although computational results are not shown here, the effect of the separation on the computational results was marginal.

3. Computational Results

3.1 Effectiveness of Proposed Scheme with Simplified Model

This section discusses the effectiveness of two excitation schemes for dosimetry in human due to contact current. In order to evaluate the computational error caused by the quasi-static approximation, we have introduced a following measure;

$$\alpha(\mathbf{r}) = \frac{|E(\mathbf{r}, f) - E(\mathbf{r}, 0)|}{E(\mathbf{r}, 0)_{\max}} \times 100 \tag{2}$$

where $E(f)$ is a strength of an electric field in a voxel and its maximal value over the body for incident wave with the frequency of f. $E(0)$ is the field strength generated by the scheme (II), since the direct current component is dominant.

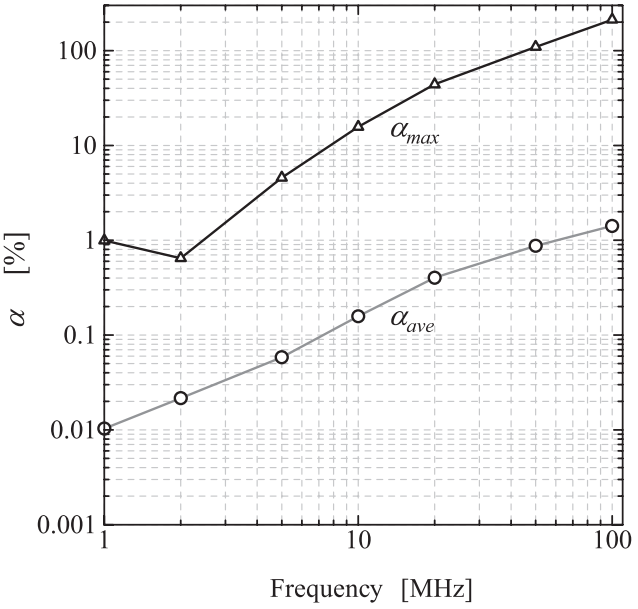

Fig. 2 Frequency dependence of global and local difference in *in-situ* electric fields for the excitation scheme (I) and (II).

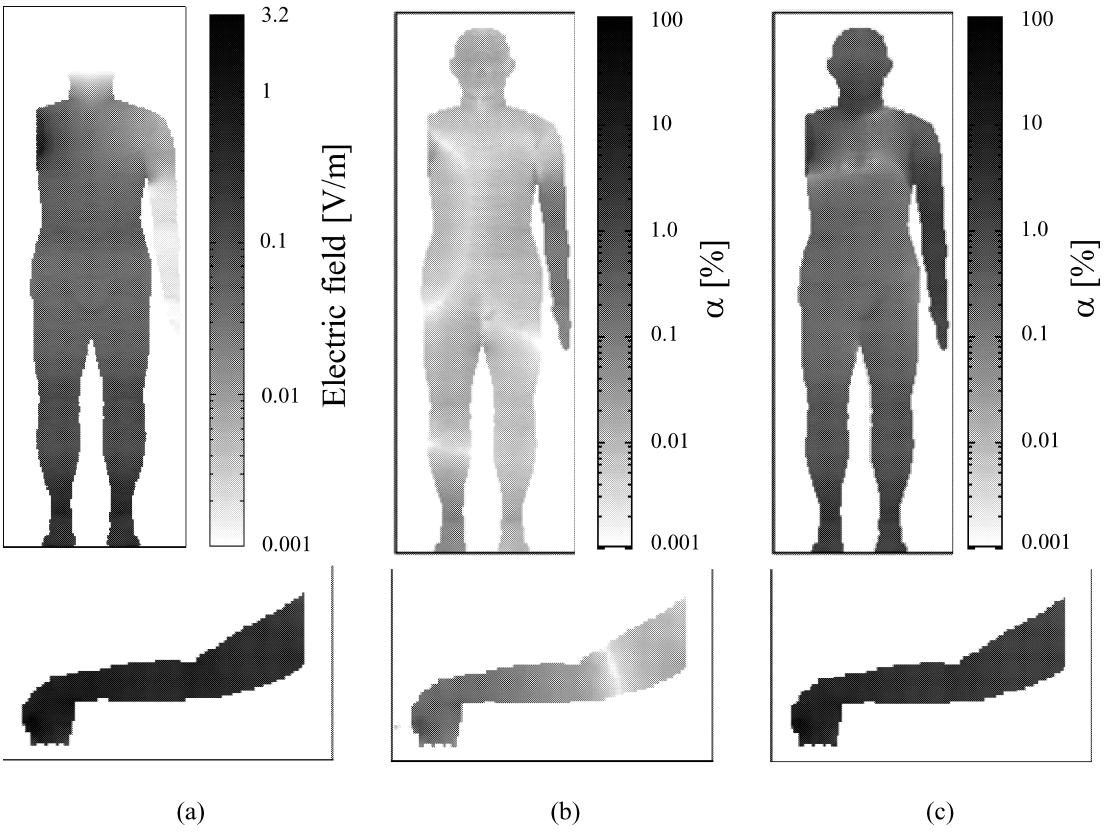

Fig. 3 Maximal value of (a) induced electric field and α projected on x-z plane at (b) 1 MHz and (c) 20 MHz. Current injected into the fingers was 0.5 mA.

The subscript 'max' represents the maximum value in human voxels. It should be noted that the error caused by the quasi-static approximation becomes larger with the increase of the frequency, since the displacement current may not be neglected. Thus, it is reasonable to consider the induced field due to the scheme (II) as an exact value.

Figure 2 shows the frequency dependency of α spatially averaged over the body and its maximal value. From Fig. 2, the difference in *in-situ* fields computed with (I) and (II) becomes larger with the frequency. Some discrepancy is observed in the frequency around 1–2 MHz. However, the magnitude of discrepancy is at most 1%. In addition, the maximal value has appeared on the surface of the figure grasping the metal piece. For direct exposure in low-frequency electric field, local maximum error has been reported to be several percents, mainly attributed to the singularity caused by using the voxel model [16]. Thus, the above discrepancy would be reasonable.

Figure 3(a) shows the maximal value of *in-situ* electric field projected on the x-z plane. Current injected into the human fingers was 0.5 mA, which is the reference level in [1]. From this figure, the *in-situ* electric field is relatively large in the right hand and ankle, while relatively small in the head and left hand. The current is injected from right hand and then flows out from the feet. Although the cross-sectional area perpendicular to the current flow depends on the body parts, the total current in the current path is almost constant from the arm to feet. For these reasons, *in-situ* electric field becomes larger in the corresponding body parts.

Figures 3(b) and (c) show the distribution of α at 1 MHz and 20 MHz, respectively. From Fig. 3(b), the value of α was the order of 0.01% in the body parts excluding extremities whereas 0.1–1% in the extremities. The value of α becomes large with the frequency. For example, the value of α is in the range between 1 and 100% in the extremities at 20 MHz. In the research field of electromagnetic dosimetry, an allowable computational uncertainty would be the order of a few dozen percents. One of the reasons for this allowance is due to the application of safety factor of 10 when deriving the safety guidelines. In addition, intercomparison at five research groups has suggested that the difference computed by different codes was 20–30% [16]. Table 1 lists the 99th percentile and average *in-situ* electric fields in the human body model for comparison. Note that the 99th percentile is a measure which is often used for low-frequency dosimetry [11]. As seen from this table, good agreement is observed for different body parts by the scheme (I) at 1 MHz while not at 20 MHz. Thus, the upper frequency which can provide allowable results would be lower than 20 MHz at least.

The main reason for introducing a quasi-static approximation to the FDTD analysis is to reduce the computa-

Table 1 Average and 99th percentile value of *in-situ* electric field due to contact current of 0.5 mA.

	Electric field [mV/m]					
	Average			99th		
Body part	Eq. (1)	1MHz sinusoidal	20MHz sinusoidal	Eq. (1)	1MHz sinusoidal	20MHz sinusoidal
Arm Left	3.88	5.57	23.1	11.5	11.8	39.5
Arm Right	320	319	232	852	855	695
Head	1.56	1.76	8.69	16.7	16.9	28.9
Leg Left	98.2	97.5	50.0	317	315	162
Leg Right	97.8	97.2	50.0	320	317	158
Torso	38.0	37.9	21.6	97.1	96.3	65.2

tional time. Let us discuss the iteration time required to computational convergence. For the condition given in the above section, the iterations were 5000 for the injection scheme (II). For sinusoidal excitation, it is known that it takes about three four periods for reaching convergence in radio-frequency dosimetry. For quasi-static approximation with higher injected frequency, the upper limit which does not take computational cost than the scheme (II) was approximately 50 MHz. However, the difference between the schemes (I) and (II) at 50 MHz may not be neglected, suggesting that the excitation scheme (II) is reasonable for the analysis of indirect exposure due to contact current. Even though we chose other models with a different resolution, this tendency may not change.

3.2 Comparison with Previous Studies

In order to verify our computational modeling, we compared our results with those by other researchers [3], [4]. In both studies, some dosimetric scenarios were considered. The human is standing in free space, and then electrodes are attached to different body parts for each scenario. The exposures condition, especially for positions at which the electrode was attached, has not been described in detail. Thus, we cannot realize an exact exposure conditions as in the previous study. In the following discussion, we considered exposure scenario given in Fig. 2. Comparison with the studies would give some insight to verify our computational results.

In [4], TARO, a standard Japanese model, was used in their computation. In this section, we chose to use this model for computation. In [3], dosimetry has been conducted for an American adult male model developed in in [17]. We chose the maximum and average electric field in the brain, heart, and spinal cord as measures for comparison. Note that the basic restriction on current density (less than 10 MHz) is applied to the central nerve tissues, such as the brain and spinal cord [1]. The reason for choosing the heart is that [3] and [4] provided data for this tissue.

From the Table 2, the difference between our results and [4] are less than 20% in heart and spinal cord. Some difference has been observed in the average value of the brain. One of the main reasons for this difference would be that our scenario considered the semi-infinite metallic plate in front of the human body (See Fig. 1). When we considered metallic thin wire instead of the semi-infinite metallic object, 99th percentile of *in-situ* electric field became closer to those in [4]; e.g., the in-situ electric field in the heart became 296 mV/m for the case of thin wire while 304 mV/m for the semi-infinite metallic plate. Another reason would be attributed to the difference in the conductivity used in our study and that in [4]. On contrary, the difference by a factor of 2 is observed between our results and [3]. One of the main factors for this difference is attributed to the model anatomy. As mentioned above, the current density or *in-situ* electric field becomes large on the current path when the cross sectional area is relatively small. Further study on the variability due to different models is needed to identify the main factor causing the difference in *in-situ* fields.

Table 2 Comparison of (a) maximum and (b) average *in-situ* electric field due to contact current at the reference level of 0.5 mA.

(a)

	Electric field [mV/m]		
Tissue	this study	[4]	[3]
Brain	4.10	3.43	1.58
Heart	304	291	97.7
Spinal cord	422	463	227

(b)

	Electric field [mV/m]		
Tissue	this study	[4]	[3]
Brain	0.633	0.165	0.15
Heart	60.9	66.3	39.5
Spinal cord	38.3	46.9	96.4

4. Conclusion

The present study proposed a quasi-static FDTD method for dosimetry in humans due to contact current at low frequencies. Our attention focused on wave sources to reduce computational time. The computational time can be reduced us-

ing a voltage source of a step function with smooth start. This computational time was smaller than the quasi-static FDTD method proposed in the previous study [8]. Our computational results and those in [4] were in reasonable agreement for the human body model named TARO, although some difference exists, which would be caused by exposure scenarios. The difference in *in-situ* electric field due to different model was by a factor of 2 or so.

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