

# IN-SITU ELECTRIC FIELDS CAUSING ELECTRO-STIMULATION FROM CONDUCTOR CONTACT OF CHARGED HUMAN

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Contact currents flow from/into a human body when touching an object such as a metal structure with a different electric potential. These currents can stimulate muscle and peripheral nerves. In this context, computational analyses of *in-situ* electric fields caused by the contact current have been performed, while their effectiveness for transient contact currents has not well been investigated. In the present study, using an anatomically-based human model, we utilized a dispersive finite-difference time-domain model to computed transient contact current and *in-situ* electric fields from a charged human. Computed *in-situ* electric fields were highly localized in the hand. In order to obtain insight on the relationship between *in-situ* electric field and electro-stimulation, cell-maximum and 5-mm averaged *in-situ* electric fields were computed and compared with strength-duration curves. The comparison suggests that both measures could be larger than thresholds derived from the strength-duration curves with parameters used in previous studies.

## INTRODUCTION

There has been increasing public concern about adverse health effects due to electromagnetic (EM) fields. Contact currents could cause indirect effects of EM fields on humans [1]–[3]. In the frequency range up to approximately 100 kHz, the flow of electric currents may result in the electro-stimulation of muscles and/or peripheral nerves. The feature of the contact current is that *in-situ* EM fields largely depend on current pathways, which is significantly different in actual scenarios [4].

When a human touches a conducting object with a different electric potential, spark discharges could occur, which produce transient current that flows from/into the human, resulting in an electric shock. Discharges associated with an electro-static field (e.g., due to walking on a carpet) are non-repetitive phenomena, whereas they could be repetitive when exposed to time-varying EM fields (e.g., 50 or 60 Hz). In that case, steady contact currents flow into the human after fully touching the conducting object.

Computation of *in-situ* EM fields/transient currents for contact currents has been conducted [4]–[8]. Dawson *et al.* reported that contact current in a steady state produce *in-situ* electric fields greater than those induced by external electric and/or magnetic fields [4]. Transient components of contact currents, or sparks, have been investigated in [5]–[8]. Amoruso *et al.* calculated the induced currents in a human body based on a circuit model consisting of lumped circuit parameters, and then evaluated currents induced in

several human body parts [5]. In that model, the model morphology is not taken into account, and thus *in-situ* current densities in specific nerve tissue cannot be calculated. Okoniewska *et al.* implemented a finite-difference time-domain (FDTD) method to simulate electrostatic discharges (ESDs) in an anatomically-based human body model [6]. In their modeling, however, the standard ESD current waveform for an ESD immunity test being specified in International Electrotechnical Commission (IEC) standard 61000-4-2 [9] was used to simulate an injected current to the forefinger. The standard ESD current waveform is known to differ from an actual current waveform (e.g., [10]). Thus, their model cannot simulate actual spark caused by the ESD event. In addition, the human tissues were simplified as non-dispersive. In order to overcome this limitation, the same group employed a frequency domain approach though the ESD current specified in IEC standard was used [7]. Furthermore, that group evaluated *in-situ* electric fields to reveal the capability of peripheral nerve stimulation in comparison with a threshold for electro-stimulation [8] defined by the strength-duration curve [11]. Note that the strength-duration curve has been derived mostly from *in-vitro* measurement (e.g., Rogers *et al.* [12]) excluding experiment on human subjects by Reilly and Larkin [13]. In these circumstances, time evolution of *in-situ* electric fields in anatomically-based human models is essential to investigate for the condition causing electro-stimulation. In addition, it has been pointed out to be important to relate incident current waveform and stimulus effect by Reilly *et al.* [14].

In the present study, using an anatomically-based Japanese adult male model named TARO [15], we utilized a dispersive FDTD model [16] to compute transient contact currents and the resultant *in-situ*

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electric fields from a charged human. Then, computed *in-situ* electric fields were compared with a threshold derived from the strength-duration curves for electro-stimulation.

## METHODS

### Computational Methods

A computational scenario was assumed that a charged human contacts a ground with a hand-held metal piece. In this scenario, we previously developed the corresponding FDTD model and verified its effectiveness by comparing with measurements [16]. Note that perceived magnitude of a capacitive discharge is much milder if the discharge occurs through a metal object rather than an arc to the finger tip. Thus, our scenario is less severe than the case assumed in the safety standards [2].

As a human body model, an adult male model named TARO [15] was used, which was developed at National Institute of Information and Communications Technology (NICT, Japan). This model is based on the magnetic resonance images of a 22-year male volunteer having a height of 1.73 m and a weight of 65 kg. The voxels were rescaled to 2-mm cubes and were segmented to define 51 kinds of discrete organs/tissues. The right arm and fingers of this body model was bent manually.

Because transient current from the charged human contains wide frequency components [5], dispersive characteristics of human tissues should be considered. Debye media can be easily incorporated into the FDTD method [17]. Therefore, we assumed that human tissues obey the dispersion properties of a four-pole Debye medium, which can be expressed as

$$\varepsilon_r(\omega) = \varepsilon_\infty + \sum_{p=1}^4 \frac{\Delta\varepsilon_p}{1 + j\omega\tau_p} + \frac{\sigma_0}{j\omega\varepsilon_0} \quad (1)$$

where  $\varepsilon_r(\omega)$  is the complex relative permittivity,  $\varepsilon_\infty$  the relative permittivity at infinite frequency,  $\sigma_0$  the DC conductivity,  $\Delta\varepsilon_p$  the change in the  $p$ -pole relative permittivity,  $\tau_p$  the  $p$ -pole relaxation time, and  $\varepsilon_0$  the free-space permittivity. For each tissue of the human body model, these parameters were determined by the least squared method in comparison with a 4-Cole-Cole model [18] in the frequency region between 10 kHz and 10 GHz. Note that Even though we chose the lower frequency as 10 kHz, our computation is expected to be reasonable for much lower frequencies. This is because tissue conductivity is almost constant at frequencies below 10 kHz, in addition that the relative permittivity can be neglected since the conduction current is dominant compared to the displacement current below 10 kHz.

Figure 1 shows an FDTD model for analyzing

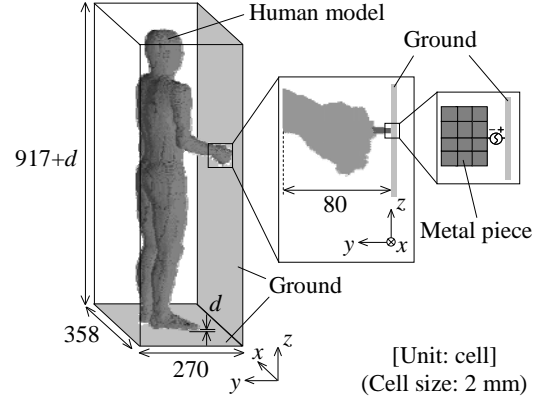


Figure 1. FDTD model used for analyses of contact currents and *in-situ* electric fields.

currents and *in-situ* electric fields. The side length of the FDTD cell was chosen as 2 mm, which coincides with the human model resolution. The human model was placed above the bottom ground at a distance of  $d = 1, 5$ , or  $20$  cells in order to change the body capacitance. The contact discharge from a charged human body to a conducting plate was assumed to be considered as an ideal switch (or shorted), which was simulated by applying a stepwise voltage source in one cell gap between the metal piece and the ground (vertical aluminum plate) as shown in figure 1. This excitation method should yield overestimation and scalable results by charge voltages. For truncation of the computational region, 12-layered PML (perfectly matched layer) was used.

### Threshold of electro-stimulation

Nerve and muscle cells can be excited by electrical stimulation. A threshold of excitation is empirically derived from a strength-duration curve [11]:

$$E_T = E_0 [1 - \exp(-t/\tau_e)]^{-1} \quad (2)$$

where  $E_T$  denotes the threshold electric field,  $E_0$  the minimum (rheobase) threshold,  $\tau_e$  the strength-duration time constant,  $t$  the pulse duration. For the peripheral nerve, values of  $E_0$  and  $\tau_e$  were listed as 6.15 V/m and 0.149 ms [2][11], while 3.6 V/m and 0.36 ms [8], respectively, which are named here Types A and B, respectively, and were used to estimate the threshold of electro-stimulation.

## RESULTS

Figure 2 shows computed waveforms of the contact currents through a hand-held metal piece from a human with a charge voltage ( $V_C$ ) of 1 kV at  $d = 1, 5$ , and  $20$  cells. The contact current consists of a steeply rising

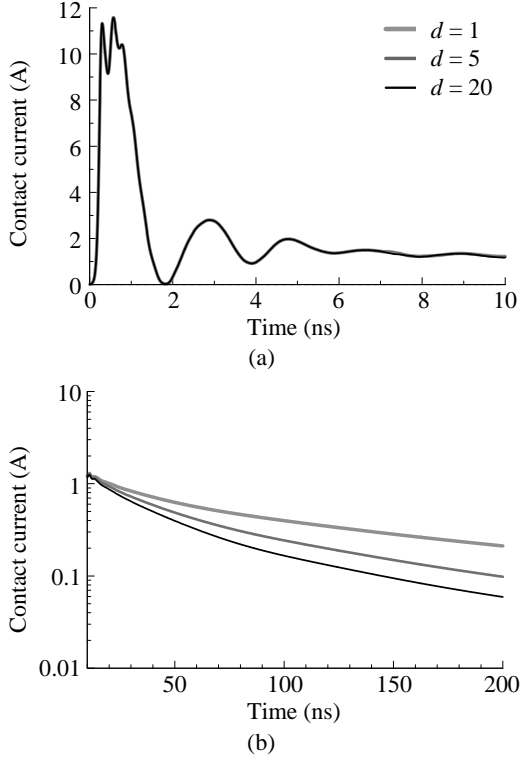


Figure 2. Computed waveforms of contact currents from a charged human with different separation of  $d = 1, 5, 20$  cells at  $V_C = 1$  kV. (a) Linear plot for 0 to 10 ns and (b) log plot for 10 to 200 ns.

current pulse and a slowly falling current. The first part of the current is generated by the discharge from stray capacitance between the metal piece and the ground, and the second current is due to the discharge from the body capacitance. As seen from figure 2, current decaying time increases with the body capacitance, while the first currents are marginally affected by the body capacitance. The rise time of the current was the order of one hundred picoseconds or so, which was comparable to the measured value [16].

*In-situ* electric fields in the right hand of the human model were computed in order to discuss electro-stimulation. Figure 3 shows (a) the image of the right hand with the metal piece and (b) distribution of *in-situ* electric fields on the right hand without the metal piece at 50 ns for  $d = 1$  cell with  $V_C = 1$  kV. As seen in figure 3(b), *in-situ* electric fields are large in the first and second fingers which contact the metal piece, and also around the wrist because of the smaller cross-sectional area than that of the palm.

Because of finite resolution and stair-casing approximation of the human model, the computed maximum electric field in one cell may contain non-

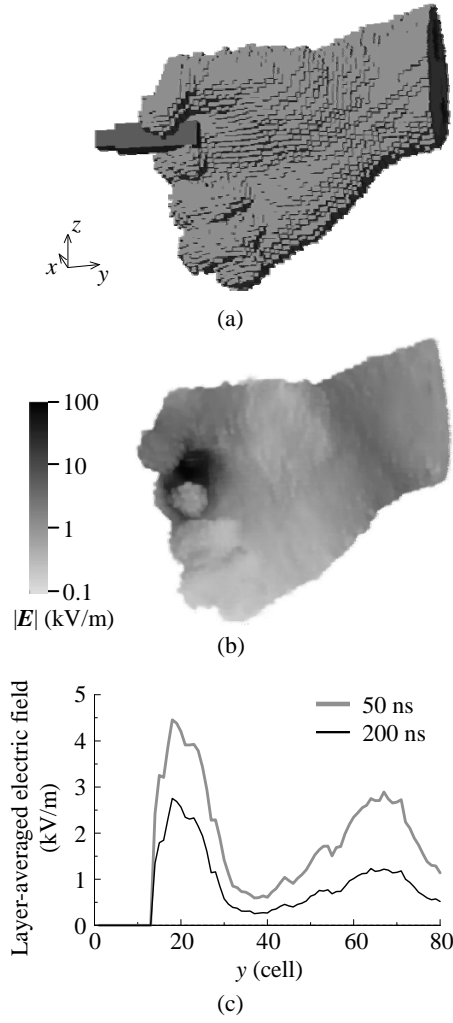


Figure 3. (a) The image of the right hand with the metal piece, (b) distribution of *in-situ* electric fields on the right hand without the metal piece at 50 ns and (c) layer-averaged electric fields at 50 and 200 ns for  $d = 1$  cell with  $V_C = 1$  kV.

negligible numerical uncertainties especially around fingers [19]. Thus, in order to obtain some tendency and empirically evaluate *in-situ* electric fields for electro-stimulation, we computed layer-averaged electric fields. In particular, electric fields in the skin and fat cells were averaged over the vertical ( $x$ - $z$ ) plane in each  $y$ -coordinate, under the assumption that peripheral nerves in the body surface tissue are stimulated. Skin cells touching the metal piece were excluded for averaging fields. Figure 3(c) shows layer-averaged electric field at 50 and 200 ns. From this figure, the above-mentioned tendency can be

confirmed. In particular, the layer-average electric field peaks at  $y = 20$  and  $70$  cells. The reasons for the peaks are that the skin touches the metal piece around  $y = 20$  cells, while cross-sectional area of the wrist is small around  $70$  cells.

Reilly and Larkin [13] reported that a minimum charge threshold is  $0.26 \mu\text{C}$  for the finger tapping an electrode connected to an anodal-charged capacitor, and also that the thresholds for cathodal stimulation were 25 to 30 percent lower than those for anodal stimulation (i.e.,  $0.18$  to  $0.20 \mu\text{C}$ ). Because their experimental condition is not identical to our FDTD model in which the human holds the metal piece, their results cannot be directly comparable. However, we only use their constant charge threshold as a reference value to obtain some insight on a relationship between the constant charge threshold and *in-situ* electric fields.

Based on the constant charge threshold of  $0.18 \mu\text{C}$ , the charge voltages of  $1.0$ ,  $1.7$ , and  $2.2 \text{ kV}$  were calculated from the computed body capacitance of  $174$ ,  $105$ , and  $82 \text{ pF}$  for  $d = 1$ ,  $5$ , and  $20$  cells. Figure 4(a) shows the time course of cell-maximum *in-situ* electric fields in the layer of  $y = 18$  cells (the layer of the maximum value in figure 3(c)) at  $d = 1$ ,  $5$ , and  $20$  cells. The horizontal axis indicates the elapsed time and can be approximately regarded as the pulse duration. Thus, strength-duration curves are drawn as rough indication of the threshold electric fields assuming that the *in-situ* electric field waveform is regarded as a square wave at the corresponding time. As seen in figure 4(a), the cell-maximum *in-situ* electric fields for different  $d$  based on the constant charge threshold were approximately overlap at a few hundreds nanoseconds, and could be larger than the thresholds given by (2) with the parameters of both Type A and B. For  $t \ll \tau_e$ , the product of  $E_0$  and  $\tau_e$  becomes constant, which corresponds to the constant charge threshold [11]. Thus, we computed time integral of *in-situ* electric fields. Figure 4(b) shows the comparison between the thresholds of  $E_0 \times \tau_e$  and the time integral of cell-maximum and 5-mm averaged *in-situ* electric fields in the layer of  $y = 18$  cells for  $d = 1$  cell. Note that the 5-mm averaged *in-situ* electric field is a metric used in [2]. From figure 4(b), both measures were larger than the thresholds of  $E_0 \times \tau_e$  with the parameters of both Type A and B.

## DISCUSSION

The effectiveness of strength-duration curves has been verified for a pulse of near  $1 \text{ ns}$  in innervated frog muscle stimulation experiments [12]. In that study, the current density was simply calculated by the current divided by estimated contact area of electrode and muscle. Thus, the necessity of the computational dosimetry has been pointed out by the authors as well as Reilly *et al.* for different applications [14]. The present study demonstrated dosimetry for electro-

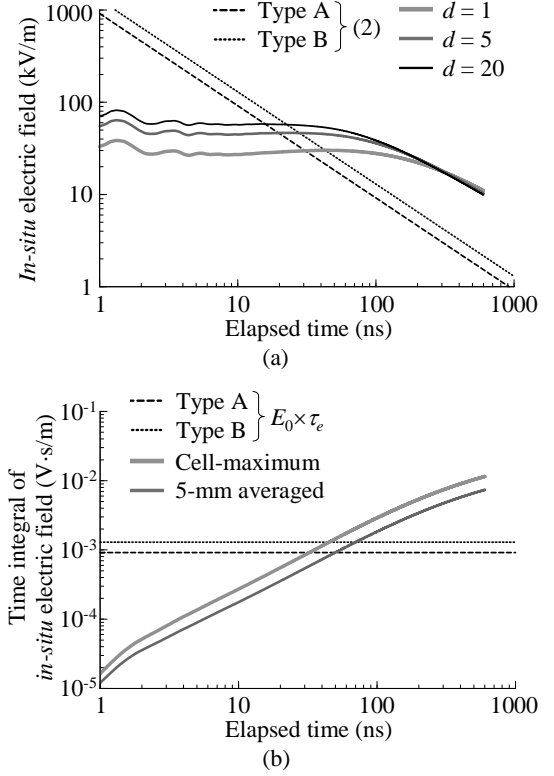


Figure 4. (a) Computed cell-maximum *in-situ* electric fields in the layer of  $y = 18$  cells at  $d = 1$ ,  $5$ , and  $20$  cells. The charge voltages for  $d = 1$ ,  $5$ , and  $20$  cells were  $1.0$ ,  $1.7$ , and  $2.2 \text{ kV}$ , which determined from the computed body capacitance and the constant charge threshold of  $0.18 \mu\text{C}$  [13]. Strength-duration curves were drawn as rough indication of thresholds. (b) Comparison between constant thresholds of  $E_0 \times \tau_e$  and computed time integral of cell-maximum and 5-mm averaged *in-situ* electric fields in the layer of  $y = 18$  cells at  $d = 1$  cell.

stimulation caused by transient contact currents. In our computation, however, there were the main three uncertainty/variability factors. The first one is the singular behavior of electromagnetic field, especially for low-frequency component, caused by using stair-casing model [19]. The second factor is the spatial averaging methods of *in-situ* electric field. Bahr *et al.* suggested that average current density/electric field is largely influenced by the averaging area of  $1 \text{ cm}^2$  [20], which is suggested in [1]. However, for *in-situ* electric field, the variability due to different averaging straight line/volume over  $5 \text{ mm}$  is at most a few dozen percents [21]. The other factor is the difference of the charge thresholds of the electro-stimulation, which is attributed to experiments condition such as electrode size [13]. The values of the minimum charge threshold for perception of short duration pulses are varied from  $0.12 \mu\text{C}$  [22] to  $0.88 \mu\text{C}$  [23].

## CONCLUSION

Electro-stimulation due to the transient component of the contact current has been commented on in the safety guidelines/standards and related documents [1]-[3]. However, *in-situ* electric field due to transient contact current was not well been investigated. Dosimetry in human for contact current was highly desirable, as pointed out by Rogers *et al.* for *in-vitro* measurement exposed to UWB pulses [12] and Reilly *et al.* for currents of electrical stun devices [14]. In order to investigate *in-situ* electric fields for electro-stimulation, we computed transient contact currents and *in-situ* electric fields in a hand from a charged human with an anatomically-based human model. The computed *in-situ* electric fields show a highly localized distribution. Because a FDTD-based evaluation has some computational uncertainties which are attributed to stair-casing approximation, *in-situ* electric fields of the cell-maximum, 5-mm averaged and layer-averaged value in a layer were computed as measures. These two measures were scaled by the charge voltages calculated from the body capacitances and the charge threshold in [13], and compared with the strength-duration curves. As a result, the cell-maximum and 5-mm averaged *in-situ* electric fields were larger than the threshold, suggesting the capability of electro-stimulation. Although, there are some uncertainty factors, computed *in-situ* electric fields could give the appropriate order comparing to the thresholds given by the strength-duration curves.

Future work is to conduct computational dosimetry in the scenarios considered to derive parameters for strength-duration curves.

## FUNDING

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