Modeling of ESD-Induced Ultra-Wideband Noise Propagating on the Human Body

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***Abstract*—Impulsive electromagnetic waves are produced when a grounded human touches a conducting object with different potential. An experimental setup was designed to measure electromagnetic fields on humans caused by sparks. The measured and computed waveforms are in good agreement. Specifically, measured and computed rise times of a discharge current were approximately 100 ps for a charge voltage of 1 kV. The generated electromagnetic pulses were distorted and dissipated with propagation due to dispersive characteristics of the biological tissues and multi-reflection in the human body. Computational results suggest that the pulse propagates over the body and is emitted from the top of the head in 10 ns.**

***Index Terms*—computational electromagnetics, electromagnetic propagation, electrostatic discharge, biological effect of radiation**

I. Introduction

When a human touches a conducting object with a different electric potential, electrostatic discharge (ESD) or spark occurs, which generates a transient current that flows from/into the human, resulting in electric shock. Discharges associated with an electrostatic 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) [1]. Electromagnetic pulses generated by ESD events have extremely wide frequency bandwidth or short rise time. In addition, multiple sparks may occur when a human without a conducting object touches a metallic object with a different potential [2].

Recently, ultra-wideband (UWB) communication systems have been studied extensively [3]. Electromagnetic pulses generated by ESD events may influence such wireless body-area network communication systems. However, the propagation characteristics of such pulses on the human body have not as yet been investigated. Electro-stimulation due to ESD has been widely investigated for human protection from electromagnetic fields. For example, the finite-difference time-domain (FDTD) modeling [4] of electromagnetic dosimetry can be found [5], in which the human body is assumed as non-dispersive medium [5].

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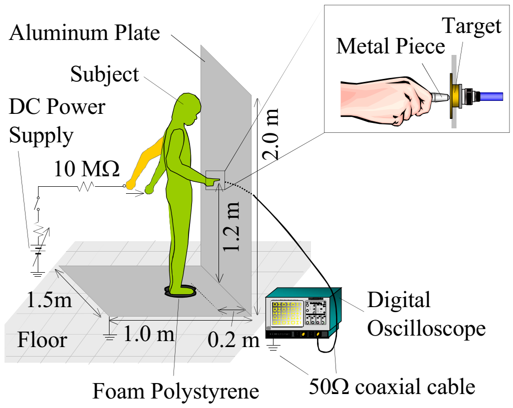

Fig. 1. A subject holding a piece of metal stood on a 1-cm-thick foam polystyrene pad for insulation from the ground. An aluminum plate (2 m × 1.5 m) was placed vertically as a ground on an aluminum plate (1 m × 1.5 m) below. The target and a digital oscilloscope were connected through a coaxial cable to measure the discharge current.

In the present study, we investigate experimentally and computationally the propagation of UWB electromagnetic pulse caused by the ESD in the human.

II. Methods

A. Experimental Setup

The experiment in the present study has been approved by the research ethics committee of the Nagoya Institute of Technology. A subject or volunteer holding a metal piece stood on a 1-cm-thick foam polystyrene pad for insulation from the ground, as shown in Fig 1. For the metal piece, we used a cylindrical metal bar 50 mm in length with a hemispheric tip and a diameter of 8 mm, which is used as a tip electrode for air discharges in IEC (International Electrotechnical Committee)-specified electrostatic discharge generators [6]. An IEC current calibration target was fixed to a 1.2-m high vertical aluminum plate connected through a 50-Ω coaxial cable to a digital oscilloscope (12 GHz bandwidth, 40 GHz sampling). The human volunteer was 1.77 m in height and weighed 60 kg.

Table 1. Parameters for electrical constants of major human tissues.

Tissue	σ_0 (mS m^{-1})	ε_∞	$\Delta\varepsilon_1 \times 10^3$	$\Delta\varepsilon_2 \times 10^3$	$\Delta\varepsilon_3$	$\Delta\varepsilon_4$	τ_1 (μs)	τ_2 (ns)	τ_3 (ns)	τ_4 (ps)
Blood	700	7.10	3.98	1.11	33.5	52.9	0.173	41.3	2.01	7.96
Bone cancellous	81.0	4.23	2.75	0.259	121	14.8	15.6	260	16.3	11.4
Bone cortical	20.1	3.17	0.411	0.124	80.0	9.14	10.1	185	25.7	11.4
Cerebellum	120	5.46	39.4	2.16	684	41.4	13.4	530	9.46	8.38
Fat	22.0	2.81	18.6	0.0840	19.1	2.66	72.7	994	17.2	8.84
Grey matter	100	6.55	29.9	2.88	524	46.0	12.7	771	11.4	8.38
Heart	120	5.91	93.5	4.27	166	50.9	9.75	161	3.51	8.84
Liver	40.0	6.18	44.7	5.39	266	40.7	12.6	263	11.4	8.38
Lung	210	6.38	56.5	4.73	851	44.7	14.5	703	42.9	8.84
Muscle	320	6.77	27.2	6.92	355	46.0	11.6	267	28.2	7.96
Nerve	28.0	5.43	60.2	3.06	351	26.2	14.4	427	16.5	8.84
Skin	0.200	4.04	0.504	0.520	54.3	35.5	0.0801	15.7	1.39	7.96
White Matter	60.0	6.39	25.4	1.33	175	31.5	14.7	354	6.12	8.84

B. Computational Modeling

In order to simulate the experimental condition, the FDTD method was used. As a human body model, an adult male model named TARO was used [7]. This model is based on magnetic resonance images of a 22-year-old male volunteer having a height of 1.73 m and a weight of 65 kg. The resolution of this model is 2 mm. The right arm and fingers of this body model were bent manually to match the measurement setup. An aluminum plate (1.5 m × 2 m) was placed vertically on an aluminum plate (1.5 m × 1 m) as a ground.

The contact of a charged human body with a conducting plate was simulated as a hard source of one-cell gap for an equivalent voltage [2] in the FDTD domain. A voltage estimated from the measured discharge current and the frequency characteristics of human body impedance were inserted as an equivalent voltage [2].

$$v_s(t) = V_C - \frac{1}{2\pi}\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}\{Z_0 + Z_B(j\omega)\}\cdot i(\tau)\times e^{j\omega(t-\tau)}d\tau d\omega \quad (1)$$

where Z_B and $i(t)$ are measured human body impedance and measured discharge current, respectively. V_c and Z_0 are the charge voltage and the source impedance (=50 Ω). Note that Z_B was measured with a network analyzer instead of the digital oscilloscope in Fig. 1.

In order to take into account dispersive characteristics of biological tissues, we used a dispersive FDTD method [8]. Wideband characteristics of biological tissues are reported in [9], in which a Cole-Cole model is used. However, a Cole-Cole model is not directly applied to a dispersive FDTD model [8]. Thus, human tissues are assumed to obey the dispersion properties of a four-pole Debye medium, which can be expressed as

$$\varepsilon_r(\omega) = \varepsilon_\infty + \sum_{p=1}^{4}\frac{\Delta\varepsilon_p}{1 + j\omega\tau_p} + \frac{\sigma_0}{j\omega\varepsilon_0} \quad (2)$$

where $\varepsilon_r(\omega)$ is the complex relative permittivity, ε_∞ the relative permittivity at infinite frequency, σ_0 the DC conductivity, $\Delta\varepsilon_p$ the change in the p-pole relative permittivity, τ_p the p-pole relaxation time, and ε_0 the free-space permittivity. The parameters in (1) were determined by the least squared method

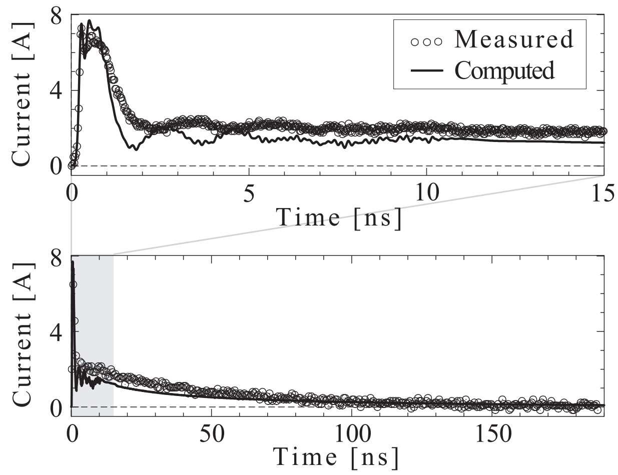

Fig. 2. Measured and computed discharge current waveforms

by comparing the data in [9] from 10 kHz and 10 GHz. Even though we chose the lower frequency as 10 kHz, our computation would be reasonable for much lower frequencies. The rationale for this is that the role of relative permittivity on electromagnetic modeling is not essential at frequencies lower than a few megahertz, since the amplitude of the displacement current is much smaller than that of the conduction current. Thus, our modeling would be applicable to much lower frequencies than 10 kHz. Table 1 summarizes the electrical constants for major human tissues determined by the above-mentioned procedure. Similar human modeling in GHz region only can be found in other literature [10, 11]. One of the limitations of our modeling is that the anisotropy of the electrical constants of biological tissue is not taken into account [9]. The relative permittivity and conductivity of air are 1 and 0, respectively.

III. Results

Figure 2 shows discharge currents through a hand-held metal piece from a human with a charge voltage of 1 kV. In this figure, the computed waveform with the voltage source (1) in addition to the measured waveform are plotted for comparison. The

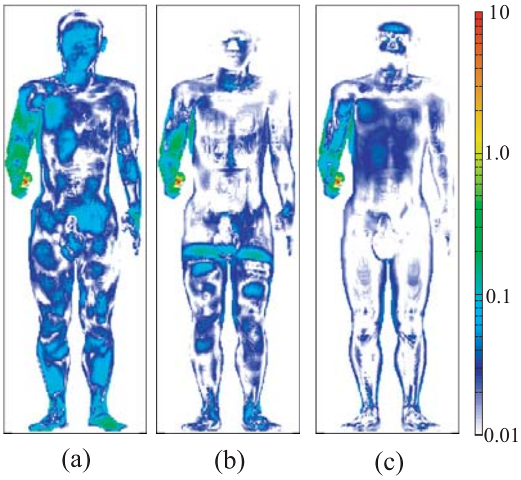

Fig. 3. The computed surface current density [A/m^2] on the human body due to the electromagnetic pulse emitted from the discharge: (a) 3.8 ns, (b) 6.3 ns, and (c) 9.5 ns.

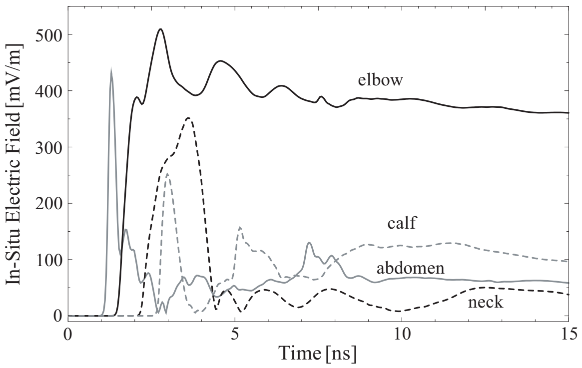

Fig. 4. Time evolution of *in-situ* electric field in the skin at different body parts. The heights of abdomen and calf were 1.0 m and 0.35 m from the ground.

contact current consists of a steeply rising current pulse (~2 ns) and a slowly falling current (a few nanoseconds). 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. The rise time and duration of the electromagnetic pulse is 100 ps and 2 ns, which are comparable to the measured results [2]. This pulse width is comparable to those used in a UWB communication system [3].

Figure 3 illustrates the time course of the surface current density. Large current density appears only around the arm. The time when the peak electromagnetic pulse reaches the sole was about 4 ns, corresponding to the distance of 1.33 m for a wave traveling at the speed of light in free space. A straight-line distance from the spark to the sole was 1.1 m, while its physical length along the arm, torso, and leg was 1.8 m. Thus, the electromagnetic pulse generated by the spark is partly emitted to free space and then propagates along the body as a surface wave. The pulse was reflected at the soles and then moved toward the top of the head. Finally, a part of the pulse was emitted from the top of the head at 9.7 ns. It took 5.9 ns for the pulse to propagate from the sole to the head, suggesting that the pulse propagates on the human body as a surface wave at almost the speed of light in free space.

Figure 4 shows the time evolution of the electric field on the human body surface at different positions in order to further discuss the propagation of the pulse. As shown in Fig. 4, the first and second peaks of the field amplitude at the abdomen were 1.3 ns and 7.2 ns, corresponding to the wave propagation in free space and the human body. The wave partially propagates along the body and is partially emitted in the free space, and then the mixed waves are observed at each position. The generated electromagnetic pulses were found to be distorted and dissipated with propagation due to dispersive characteristics of the biological tissues and multi-reflection in the human body.

Let us discuss the energy balance in the ESD event in order to further obtain some insight into this phenomenon. First, human body capacitance was computed in order to estimate the electrostatic energy before the ESD event. The human-body model was assumed to be comprised of a perfect conductor that was then charged at the voltage Vc. The induced electric charge on the human body surface Q was computed and the human body capacitance was estimated as Q/V_c. For the human-body model 10 mm from the ground, the estimated value was 105 pF, which is in good agreement with measured values of 120 to 130 pF [12]. Thus, at a charge voltage of 1 kV, the static energy stored in the human body was 52.5 μJ. Energies dissipated in and radiated from the human body were 49.5 μJ and 3.0 μJ, respectively.

IV. Conclusion

In the present study, an ultra-wideband electromagnetic pulse caused by an ESD event was investigated experimentally and computationally. The generated electromagnetic pulses were distorted and dissipated with propagation due to dispersive characteristics of biological tissues and multi-reflection in the human body. Computational results suggested that the pulse propagated over the body and radiated from the top of the head in 10 ns. Future work will be to investigate the influence of such pulses on wireless communications system used around the human body, in addition to the assessment of human safety for the ESD [1].

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