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Electromagnetic interference risk from electrostatic discharge in infant incubators

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ABSTRACT

This paper proposes an improved electromagnetic compatibility (EMC) risk analysis approach for medical equipment related to the effect of electrostatic discharge (ESD). This approach not only focuses on the risk of ESD from the susceptibility aspect but also investigates its conducted electromagnetic interference (EMI) characteristics. This study combines the standardized ESD test and conducted emission (CE) measurement simultaneously, applying it to the infant incubator and analyzing the spectrum of ESD current in the phase line in the time and frequency domain. The result shows that an ESD exposure caused current spikes with an average level of 13.8 A. Moreover, it also causes a broad spectral CE noise on the phase line of the infant incubator. Furthermore, the CE noise in the low-frequency range was also detected on the phase line during ESD exposure, indicating the risk of interference with other sensitive medical equipment connected to the same power network. The approach of proposed risk analysis in this study can be used to identify the risks of EMI due to ESD events in implementing the latest IEC 60601-1-2.

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1. INTRODUCTION

A hospital is a complex system comprising several interconnected medical equipment; this condition leads to destructive interference of electromagnetic waves [1], [2]. As the number of medical equipment installed in one care unit increases, the probability of electromagnetic interference (EMI) increases [3]-[5]. This interference can lead to erroneous data, equipment malfunction, and even failure of life-sustaining equipment, posing a serious threat to patient and healthcare safety. Understanding and mitigating EMI risks are crucial for ensuring the integrity and reliability of healthcare delivery in hospitals.

Reliable performance and quality of medical equipment are essential to ensure the safety and effective measurement in providing high-quality healthcare to patients. In any healthcare facility, medical equipment is expected to operate normally without any performance degradation (susceptible) and without generating unwanted EMI noises [3], [5]. This is because many medical devices are designed with high sensitivity to detect patient's bioelectrical signals. Thus, most of these medical equipment work in a very low-frequency range (DC-20 kHz) with very low voltage levels (μV–mV order) [6], such as electroencephalogram (DC-100 Hz), electrocardiogram (0.01 Hz-250 Hz), electromyogram (20 Hz–1 kHz), and electroneurogram (250 Hz–6 kHz). It makes the reading result and the performance of these medical equipment prone to low-frequency EMI. Low-frequency noise in the form of unwanted conducted emission (CE), such as hum noise, harmonic, random noise from the power line (120 Hz up to 10 kHz), or any signal in this frequency range can disturb the signal processing and original data of bioelectrical signal recorded by these sensitive medical equipment [7].

CE refers to the transmission of EMI through conductive materials such as electrical power cables, signal lines, shared grounding, or other conductors [8]-[10]. Low-frequency CE EMI is caused by several sources within the hospital ecosystem, such as power line noise from electrical equipment [7], installation of non-linear loads, and high dV/dt or dI/dt from the switching mechanism of any medical equipment. As an example, the switching mechanism to control the temperature of infant incubators [5], [11]. It is reported that the quasi-peak of EMI generated from this mechanism is quite high, reaching 92.9 dBμV. Several studies have reported the effect of CE interference on sensitive medical equipment, such as artifacts in ultra-sonic diagnostic equipment [12], causing malfunction in nerve stimulation equipment [13], and weakening diagnostic medical equipment [14].

In mitigating EMI risks, identifying all aspects related to electromagnetic compatibility (EMC) is essential due to the emission from medical equipment and its susceptibility [15], [16]. All CE behavior when the equipment is operated or in steady condition should be observed carefully, including when an electrostatic discharge (ESD) event [13], [17]. An ESD event can happen when an operator or a patient who has accumulated static electricity touches a medical device, causing the built-up charge to discharge into the equipment rapidly. Regarding the effect of ESD on medical equipment, a report by [18] shows that from January 2010 to May 2020, 1342 cases of medical equipment were related to ESD [19].

Due to the importance of investigating the ESD effect on medical equipment, this study looked into the effect of ESD on CE noise generated by medical equipment in correlation with high transient currents that flow through the conductive materials of medical equipment. Previous studies have investigated the impact of ESD. However, most of them only investigate the susceptibility aspects, such as unexpected reset, alarm, malfunction, or damage [19]-[21]. To the best of the authors' knowledge, only one study in [21] has investigated the current and voltage behavior of medical equipment under ESD exposure. It was found that the ESD can significantly increase the level of current and voltage on wearable medical equipment [21]. It was also found that a lower impedance will increase the level of measured current. However, [21] did not analyze further the spectral component of the current and voltage, which makes the effect of ESD on the CE noise that appears in the working frequency range of medical equipment not yet revealed.

This study takes an infant incubator as equipment under test (EUT). This is because ESD events frequently occur when healthcare operators make contact with this equipment. The metal structure of the infant incubator is the current path with low impedance, increasing the probability of an ESD event. The remainder of this paper is structured as follows; section 2 presents the ESD testing methodology employed to test the infant incubator. Section 3 presents the measurement results and discussions of the CE of the infant incubator during the ESD test. Finally, the conclusion is given in section 4.

2. METHOD

In investigating the ESD effect on the CE spectral of the infant incubator, this study combines standardized ESD testing with CE measurement. The setup of ESD testing refers to IEC 60601-1-2 [22], IEC 60601-2-19 [23], and IEC 61000-4-2 [24]. The ESD gun with a round tip is connected to the ESD generator. The operator sets the level of ESD through the PC. Five ESD levels are applied in this investigation: they are 6 kV, 8 kV, 10 kV, 12 kV, and 15 kV. The ESD voltage levels represent the electrical potential energy accumulated on the ESD gun tip. The points of the infant incubator subject to ESD shots are the points that are identified as accessible parts. In total, nine points are selected; they are the handles for moving (6 points), the incubator's control panel (1 point), and the handle to open the chamber cover (2 points).

In this research, ten times air discharge ESD shots were applied to each level, and each point of the infant incubator with a 1 s delay of each discharge. During each ESD shot, the performance of the incubator was observed, and any performance degradation was recorded. At the same time, the current waveform at the phase line ~~is~~ was measured using two current probes. Current probe TA 189 from Pico technology and Texbox TBCP1 were used to measure the current characteristic at low-frequency component (0-100 kHz) and I_{spike} at higher frequency (10 kHz-250 MHz), respectively. Both current probes were connected to a multichannel oscilloscope 4824A from Pico technology. Measurements in these two frequency ranges are needed to capture the transient characteristic of ESD current, which has a broad spectrum range. The recorded data is then analyzed in the time and frequency domain. The setup of the ESD testing and CE measurement is shown in Figure 1.

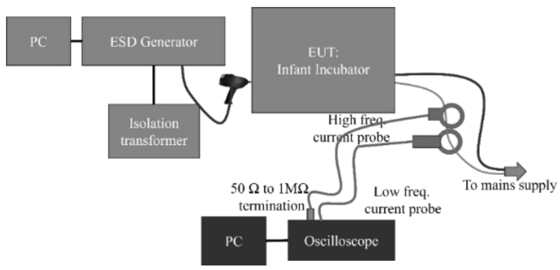


Figure 1. ESD test and CE measurement setup

The effect of ESD on low-frequency CE was analyzed in the 3-D spectrogram. The 3-D spectrogram illustrates the graphical interface of the current on the phase line in the time and frequency domain simultaneously. This spectrogram was obtained by processing the data using short-time Fourier transform (STFT) with Hamming windows. Refers to [25], the observed frequency range is DC-20 kHz. Based on [26], the STFT formula is stated as (1), with the total sampling points at 100000, by sliding the analysis window $g(n)$ with a length of the window (m) of 1000 by interval (R) of 100 samples. All of this computing process was executed with a MATLAB code.

$$X_m(f) = \sum_{n=-\infty}^{\infty} x(n) g(n - mR) e^{-j2\pi fn} \tag{1}$$

3. RESULTS AND DISCUSSION

During the ESD test, an alarm occurs when the incubator is exposed to 12 kV and 15 kV ESD at point 4. Furthermore, when looking deeper at the CE analysis, mainly on the current waveform on the phase line, we found that each ESD event has a strong correlation with I_{spike} appearing on the phase line, as shown in Figure 2. The following mechanism can explain the presence of I_{spike} ESD current on the phase line. The injected high-voltage ESD creates currents that propagate through the incubator structure and then flow through the ground wire to find the point of lowest potential where the ground wire is tied to the earth. Because in a 3-wire cable, the phase, neutral, and ground wires are tightly bundled, the current flowing through the ground wire is strongly coupled to the phase and neutral wires. Therefore, the coupled ESD currents are observed in the phase wire as I_{spike}.

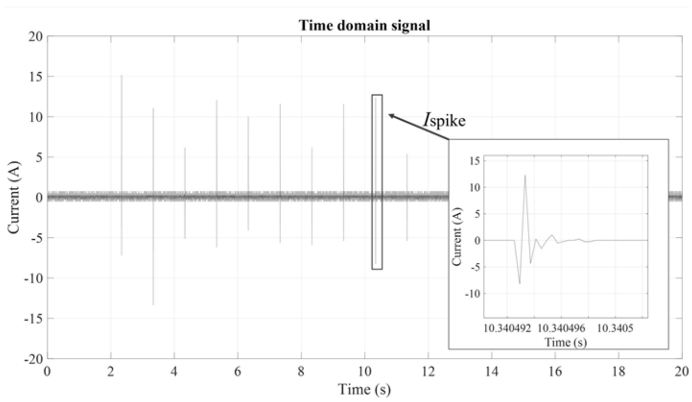
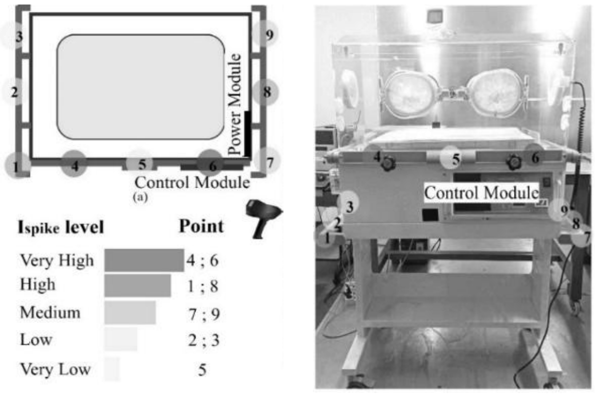


Figure 2. I_{spike} on the phase line

Our findings indicate that ESD shots at nine different points of the infant incubator resulted in different levels of I_{spike} in the phase line. This is due to the level of ESD current that flows through the phase line depending on the path of ESD current and material impedance ($Z_{\text{EUT}}=R_{\text{EUT}}+jX_{\text{EUT}}$) [27]. Figure 3 shows the incubator's ESD test points and the average of I_{spike} at the phase line due to ESD disturbance at nine test points is shown in Figure 4. Furthermore, the correlation of ESD current (I_{ESD}) and induced voltage (V_{induced}) can be stated as (2) [28]. Where the $T(j\omega)$ is the coupling transfer impedance function.

$$V_{induced} = T(j\omega)^{-1}.I_{ESD} \tag{2}$$

In Figures 3(a) and (b), the risk in terms of I_{spike} level is depicted in grayscale, where light and dark grey represent low and high risk, respectively. Figure 3(a) shows the top view of the ESD test point applied to the infant incubator. It shows ESD at different points, resulting in different effects on the level of I_{spike}. Furthermore, Figure 3(b) shows the front view of the ESD test point applied to the infant incubator. Figure 4 shows that I_{spike} tends to be higher when the ESD level is increased. As a comparison, ESD on point 4 with a discharge level of 15 kV resulting I_{spike} 7.6 A higher than ESD at the same point with a discharge level of 6 kV. However, the effect of the ESD level on the I_{spike} of each point is different. Point 6, as an example, increasing the ESD level from 6 kV to 15 kV only increases I_{spike} 6.6 A. On the other hand, increasing the ESD exposure level on point 5 tends to have a significant effect. Furthermore, Figure 4 shows that points 4 and 6 generated the highest I_{spike}. Under 15 kV, the average I_{spike} on the phase line as a result of ESD on point 4 is 13.8 A, and the average I_{spike} as a result of ESD on point 6 is 11.25 A. This happens because points 4 and 6 have the lowest path impedance to the power and control module and eventually to the ground wire. Meanwhile, the lowest average I_{spike} of 0.79 A occurs at point 5. This point is the handle of the incubator, which is the most accessible part of the incubator, which is metal coated with thick paint to present a higher impedance. Therefore, if any ESD event occurs at this point, the possibility of producing I_{spike} on the phase line is low.



(a) (b)

Figure 3. Map of the "ESD test points" from the: (a) top and (b) front view

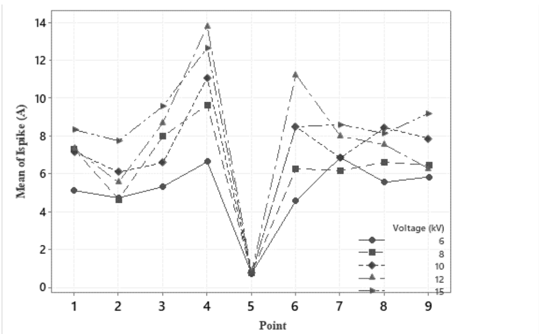


Figure 4. I_{spike} on each point

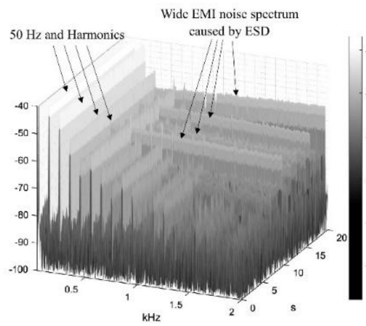


Figure 5. Map of the "ESD test points" from the top view

Further analysis of CE noise is conducted on the 3-D spectrogram of phase current. For example, the spectrogram shown in Figure 5 is the CE noise in the frequency range of 40 Hz–2 kHz observed in the phase line of the incubator during the 10 kV ESD test on point 7. It shows two different types of noises, i.e., background noise, and a wide-band additional CE noise. Background noise is generated by the incubator, which is a harmonic noise of 50 Hz that constantly appears all the time during the measurement. It appears as the result of the switching mechanism during the essential heating operation of the infant incubator. Meanwhile, additional wide-band CE noise occurs in accordance with the ESD events. Figure 5 shows that wide spectrum noise appears throughout the range from 0 Hz up to 2 kHz with similar timing of ESD events. This proves that the wide-band additional CE noise only occurs when ESD shots are applied to the infant incubator.

This research reveals that a short transient ESD has a significant effect on the CE spectrum of medical equipment, however, the result is constrained by the limited number of samples, which may not fully capture the complexities encountered in practical applications. This study has highlighted the presence of CE noise that occurs in a low-frequency range, which is the same frequency range as bioelectric signals from humans. It means that the EMI noise has an unwanted potential to interfere with the EEG signal (DC-100 Hz), ECG signal (0.01–250 Hz), or EMG signal (20 Hz–1 kHz). Future research may look into the effect of CE noise in the low-frequency range directly on medical equipment and involve an adequate sample size to ensure the generalizability and robustness of the findings.

4. CONCLUSION

This paper aims to analyze the effect of ESD on CE noise in the power lines of the infant incubator at a low-frequency range. The study was performed by simultaneously combining the ESD testing standard and CE measurement. The investigation indicates that the highest average I_{spike} on the phase line occurred when ESD was imposed on the closest point to the power module due to its low impedance path. Furthermore, the 3-D spectrogram analysis showed that wide-band CE noise due to ESD exposure was also detected in the low-frequency range. This is due to the natural characteristic of short spike current with a microsecond duration in ESD that creates additional CE noise flows on the power network. In addition, EMI risk measurements in a hospital become more important to implement the IEC 60601-1-2 risk management standard. Assessing the risk of ESD only from the susceptibility perspective is not enough; its effect on the CE noise should be considered. Therefore, the results from this research can be used to improve quality assessment in healthcare facilities by applying EMC risk management standards.

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