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Avoiding Electromagnetic Interference in Advanced Medical and Welfare Facilities

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Abstract

In future medical facilities, it is required to realize safe and high-quality medical treatment by utilizing medical electronic technology and information communication technology including medical robots. For that purpose, it is essential that medical equipment and medical systems operate stably. That is, it is important to construct the electromagnetic environment of the operation space well. Under such recognition, Consortium on Dependable Electromagnetic Environment of the National Institute of Advanced Industrial Science and Technology (AIST) published "Guidelines for Electromagnetic Environment of Advanced Medical and Welfare Facilities "(AIST18-J100019). In this paper, the electromagnetic environment standard in the operation space is shown, and the countermeasure propose shown in the guideline is introduced, referring to the related preceding study and actual measurement examples.

Keywords: Medical facilities • Malfunctions • Electromagnetic environment • Lightning protection system • Grounding system

Introduction

The development of medical care has been supported by the development of new pharmaceuticals, the progress of medical devices, and the efforts and enthusiasm of medical personnel. In altitude medical facilities, medical electronic and information communication technologies including medical robots are also utilized, and medical care is expected to make further dramatic progress [1,2].

Safety considerations common to medical electrical equipment (ME equipment) until now were protection against electric shock. However, stable operation of ME equipment will be more required in future medical facilities. However, the conventional design and construction guidelines on medical facilities are architecturally related to the layout plan and the specifications and functions of medical rooms [3] and are electrically indicated mainly on the prevention of electric shock of users and the prevention of power failure of medical power supply [4,5]. Besides, no design guideline on the electromagnetic environment is shown except for special rooms such as MRI (Magnetic resonance imaging) rooms.

Disturbances caused by electromagnetic noise in medical facilities can be classified into two categories.

First category is the mutual interference of equipment using radio waves, e.g. wireless LANs (Local area network), cellular phones, RFID (Radio frequency identifier), medical telemetry systems and ultrasonic diagnostic equipment etc. Electromagnetic compatibility conference Japan, ECCJ, reported their studies for the safe use of mobile phone in medical institutions [6]. ECCJ also published the guidelines for selection of ME equipment using the radio wave, rule in the availability, and management in the case of trouble occurrence in 2016 [7] and they were revised in 2021 [8]. These guidelines were written for the medical professionals and the communication carriers etc.

Second category is interference to medical equipment by electromagnetic noise such as unnecessary electromagnetic waves arising from ME equipment, the other equipment, such as inverter-driven equipment, and lightning surge. Recently unstable operations of medical telemetry systems have been big concern in Japan [9-11]. Muraki warned that the noise generated by LED (Light emitting diode) lightings disturbed the stable operation of medical telemetry systems [12]. Architectural institute of Japan has summarized the guidelines [13] on the design and installation of the medical telemetry systems. Electromagnetic interference between ME equipment, e.g. interference between an electro-knife and an electro-cardiogram, and their countermeasures were also reported [14,15]. Ohso et al. reported a trouble that a diagnostic image of ultrasonic diagnostic equipment were disturbed by radiation of noise from a power supply cable for inverter-driven ventilation fan [16]. Besides, it has been pointed out that the current lightning protection system is intended to suppress permanent failures of electrical equipment and does not prevent malfunction of them [17,18].

Thus, although there is an awareness of the risks caused by electromagnetic interferences in medical facilities, only countermeasures by management, and countermeasures for individual incidents have been introduced as described above. However, it is clear that we must consider the stable operation of medical facilities throughout the building. Therefore, it is important to consider the whole building as one system and construct proper electromagnetic environment in the building, but it has not been sufficiently discussed.

Under this background, this paper describes the construction method of electromagnetic environment in altitude medical facilities for safe and secure operation of medical facilities. This paper explains the electromagnetic environmental measures of a building, while citing the "operation space guideline of electromagnetic environmental guidelines for advanced electronic medical facilities" (AIST18-J00019) [19] published from AIST consortium, and relevant researches.

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Standards for ME Equipment and Medical Facilities in Japan

In Japan, the safety of electric facilities is regulated by a ministerial ordinance that establishes technical standards for electrical facilities and by interpreting technical standards for electrical facilities. In addition to these regulations, Japanese Industrial Standards have been established for medical facilities and ME equipment. On the other hand, international standards IEC 60364 series stipulate requirements of installation method of low-voltage electric equipment in demand locations. Furthermore, regarding medical facilities, IEC-60364-7-710 stipulates requirements that need to be added in hospitals and the like.

Since Japanese medical facilities are not regulated by IEC 60364-7-710, they are mainly discussed based on Japanese Industrial Standards in this paper. However, the progress and issues of medical facilities and the essence of the measures described in this paper remain unchanged.

The Japanese Industrial Standards for Medical Facilities and ME Equipment include JIS T 0601-1: 2017 "Medical Electrical Equipment-Part 1: General Requirements for Basic Safety and Essential Performance" and its standards group and JIS T 1022:2018 "Safety Requirements of Electrical Installations for Medically Used Rooms in Hospitals and Clinics". The former stipulates basic safety and essential performance of ME equipment and medical electrical systems. The collateral standard, Part 1-2: "Electromagnetic Disturbances - Requirements and Tests" indicate the requirements for electromagnetic immunity and electromagnetic emissions of the equipment and its systems. The latter stipulates safety standards and design methods for medical grounding system, non-grounding wiring system, and emergency power source among electrical facilities installed in hospitals, clinics, and the like to ensure safety in use of ME equipment. That is to say, in this standard, the approach of electric facilities in the medical room is mainly specified from the viewpoint of electric shock prevention and power failure prevention. Especially, regarding electric shock prevention measures, it is stipulated that equipotential grounding is carried out for the purpose of preventing micro shock (electric shock through the heart, or electrical shock directly to the heart). Equipotential grounding refers to grounding of metal parts (not only ME equipment but all metal parts such as fittings) within the range that a patient can touch, namely arm's reach. Equipotential grounding is provided in medical rooms where medical treatment is performed by inserting or contacting the heart directly, such as intracardiac treatment and cardiac surgical operation. Other medical rooms are also required to be provided by equipotential grounding as required. In addition, medical grounding lines shall be connected to principally building columns, while vertical dedicated medical grounding lines are also admitted, at least two points on each floor. That is to say, the lower impedance for grounding line for ME equipment is attempted by using the column and structure of the building.

Electromagnetic Environment Guidelines for Advanced Electronic Medical Facilities

The AIST consortium on Dependable Electromagnetic Environment was established with the purpose of encouraging the development of related industries, with the aim of standardizing the electromagnetic environment as one of the indispensable environmental problems for realizing safe and secure quality of life by utilizing information and communication technology and robot technology. "Utilization Space Guidelines for Robot Technology and Information and Communications Technology (AIST12-J00011)" [20] was published in 2013. Its outline is described in [21]. Afterwards, in view of the importance of construction of electromagnetic environment of medical facilities, "Utilization Space Guidelines for Advanced Electronic Medical Facilities" (AIST18-J00019) was published.

In advanced medical facilities, ME equipment is connected to the communication network, and medical information is integrated and managed. Occasionally, medical information is shared in real time during medical actions to support the judgment of the physician. And, automation and robotization of ME equipment advance at the same time, and it supports not only judgement but also medical action. That is to say, it helps the medical personnel to provide the patient with the smoother and higher quality medical treatment by the advanced computerization technology. Since it is electronic technology that is at the base of these advanced medical facilities, here, the medical facilities that provide such advanced medical services are called advanced electronic medical facilities.

In advanced electronic medical facilities, it is essential that ME equipment and medical systems be operated stably. Therefore, it is indispensable to keep the electromagnetic environment of the whole medical facility good so that the ME equipment does not cause malfunction due to electromagnetic interference. However, as outlined in Chapter 2, there are no standards related to the electromagnetic environment of the medical room or the medical space, and even if the immunity or emission of the electronic medical equipment is specified, the ME equipment is not always installed in a space that satisfies the immunity performance.

Then, the guidelines determined the following electromagnetic environment standard values in the electromagnetic environment guideline in the advanced electronic medical facility as shown in **Table 1**.

Table 1. Electromagnetic environment standard value [19].

Radiated disturbance	Standard value	Frequency
Electromagnetic field (Electric Field)	3 V/m or less (129dBµV/m or less)	80 MHz ~ 2.7 GHz
Magnetic field	30 A/m or less (r.m.s.)	50 Hz or 60Hz

These values were referenced to immunity test levels for radiated radio frequency electromagnetic fields and power supply frequency magnetic fields in JIS T 0601-1-2:2018. Medical equipment is required to have higher immunity performance than general industrial equipment. Therefore, the standard was established referring to the immunity performance of ME equipment, but this does not mean that the electromagnetic environment which is more severe than the general environment is allowed in medical facilities. In view of these points, the reference value here indicates the minimum performance, and it is necessary to aim to construct an electromagnetic environment superior to this standard.

Electromagnetic Environmental Issues in Medical Facilities

The following electromagnetic environmental problems occur in medical facilities.

1. Mutual interference between devices utilizing radio waves, such as medical telemeters, wireless LANs, and cellular phones

2. Effects of noise generated by ME equipment such as MRI and X-ray equipment on electronic equipment with weak electromagnetic resistance (electronic medical charts, medical telemeters, ultrasonic diagnostic equipment, control equipment, etc.)

3. Effects of noise generated from inverter-based equipment such as elevators, air-conditioning equipment and pumps, and LED lighting equipment on ME equipment with weak electromagnetic resistance

4. Impact on medical care due to damage or malfunction of ME equipment caused by lightning strikes and failure of infrastructure equipment such as power supply and information and communication facilities

5. Effect of radio waves used for communication of ambulances, taxis and other business and work radios on ME equipment with weak electromagnetic resistance

The impacts of these electromagnetic disturbances are not only caused by direct interference between the noise generating equipment and the affected equipment, but also by radiation from the power supply wiring of the noise generating equipment or the wiring for control, and the intrusion of the common mode noise from the structure or the grounding system.

In the medical facilities, noise sources such as electric knifes, MRI and X-ray equipment and ME equipment with weak noise resistance (electronic medical chart, medical telemeter, ultrasonic diagnostic equipment, control equipment, etc.) are installed in the same building, and therefore, the electromagnetic environment problem is in a situation easily generated. However, the electromagnetic interference between such ME equipment seems to be relatively easy to improve, because those who handle ME devices are limited to medical professionals.

On the other hand, inverter equipment used for infrastructure facilities of buildings and countermeasures against lightning strikes are easily missed by medical personnel, so it is necessary to sufficiently examine them in planning and designing medical facilities.

Principles for a Desirable Electromagnetic Environment

The guidelines propose the following principles for a desirable electromagnetic environment for medical and welfare facilities.

1. Electrical independence or separation of the equipment from other electric system: To ensure electrical independence between support structures, communication control facilities, and power facilities, metal members used in the structure shall be the minimum necessary, and the construction of an insulated structure with an insulated and non-magnetized structure shall be aimed at.
2. Suppression of electromagnetic waves (or radiating electromagnetic fields): Take appropriate electromagnetic shielding measures to suppress disturbances caused by extraneous electromagnetic waves, internal electromagnetic waves, and electrostatic discharges.
3. Suppression of magnetic fields: In order to suppress the adverse effects of the magnetic field, take appropriate magnetic shielding measures.
4. Suppression of conducted noise (insulation of the building structure from power supply and grounding system): In order to ensure electrical independence, measures such as lightning protection system, independent grounding, insulation of bar arrangement materials and metal members, installation of noise filters, and require isolation measures for electrical equipment shall be appropriately taken.

It should be noted here that it is compatible with equipotential grounding as shown in JIS T 1022. Naturally, the primary priority is to protect human body and life from any electric shock, including micro shock. However, due to the progress of ME equipment, it is naturally conceivable that the malfunction of ME equipment directly affects human life. Therefore, in the design of medical facilities, it is necessary to construct a safe medical space by ensuring both equipotential grounding and electrical independence.

Case Study

Lightning protection system

Problems of conventional lightning protection system: Lightning protection system in Japan are usually carried out according to the following two Japanese standards. One is JIS Z 9290-3: 2019 (Protection against lightning-Part3: Physical damage to structures and life hazard), and the other is JIS Z 9290-4: 2009 (Protection against lightning-Part4: Electrical and electronic systems within structures). The former is the translation of IEC 62305-3: 2010, (Protection against lightning-Part3: Physical damage to structures and life hazard), and the latter is IEC 62305-4 2010, (Protection against lightning-Part4: Electrical and electronic systems within structures). The former is partly changed in accordance with the circumstances of Japan. The former is a standard to protect against damage of buildings caused by lightning strikes and direct damage caused by lightning currents such as life crisis of human lives. The latter is a standard which defines methods for reducing electromagnetic damage (failure of electrical and electronic systems) from lightning currents.

Figure 1 schematically illustrates a conventional lightning protection system for a building. Building structures (columns, beams, made of iron rebar or steel frame) are used as down conductors of lightning protection system. The building is protected from lightning strike by air-termination system such as lightning rods and horizontal conductors. In the case lightning strike to lightning rod, the lightning current passes through the building structure, and flows toward the ground. As shown in the figure, the lightning current flows mainly through the outer columns, but at high floors a good part of it flows also through inside columns [22]. As a result, a lightning surge may intrude from the building frame to electric/electronic equipment to destroy it without surge protective devices [23, 24]. In addition, since a magnetic field forms around a lightning current by induction, the effects of electromagnetic impulses due to lightning extend to the building inside [25].

Tsuchida and Yasui et.al analyzed magnetic field distribution in a building generated in case of direct lightning strike to the building [18]. VSTL rev2.3 (CRIEPI: 2010) [26], an analysis software package based on the finite difference time domain method (FDTD method), was used for the analysis. A schematic diagram of the analyzed building is shown in **Figure 2**.

It was a five-story building, 33.5m × 22.5m × 20.5m in size. The analysis conditions are shown in **Table 2**.

The external lightning protection system, which comprises an air-termination system, a down conductor system and a ring grounding electrode, is arranged as shown in **Figure 3**.

The air-termination system consists of horizontal conductors on the 4th and 5th floor. These conductors are electrically connected to the outer columns at the roof floor. That is to say, the columns are used as down conductors. In **Figure 3**, only the columns of the outer circumference are expressed as the building structure, but the analysis is carried out using a model in which columns and beams are incorporated inside the building as shown in **Figure 2**. The magnetic field distribution in the horizontal plane 1m above the 5th floor (countered by red lines in part (**a**) of **Figure 4**, and the vertical plane including the EPS (Electric pipe shaft) (countered by red lines in part (**b**) of **Figure 4**, were analyzed. Grounding line is installed EPS, and this grounding line is connected with building structure in each floor. The lightning current waveform

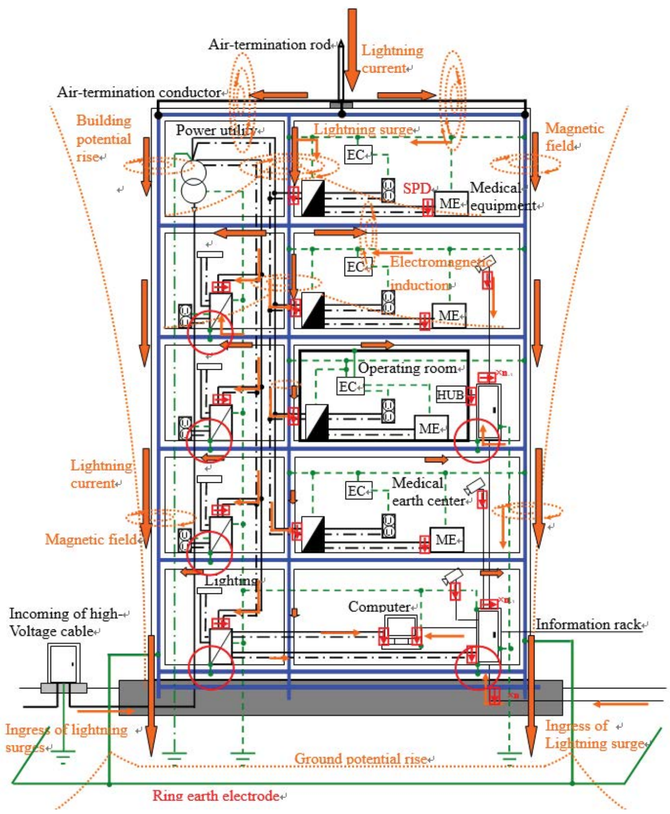


Figure 1. Example of conventional lightning protection system [19].

Table 2. Analysis condition [25].

	Description
Size of the analysis space	50 × 45 × 70 m
Cell size	0.25 × 0.25 × 0.25 m
Boundary condition	Secondary absorbing boundary surface of Liao
Depth of the earth	40 m
Resistivity of the earth	17.4 ohm m
Relative dielectric constant of the earth	10
Columns	Cylinder-conductor of 1m in diameter
Big pillars	Conducting wires of 1m in diameter
Small pillars	Conducting wires of 0.5m in diameter

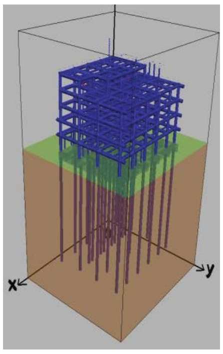


Figure 2. Schematic diagram of calculated building model [25].

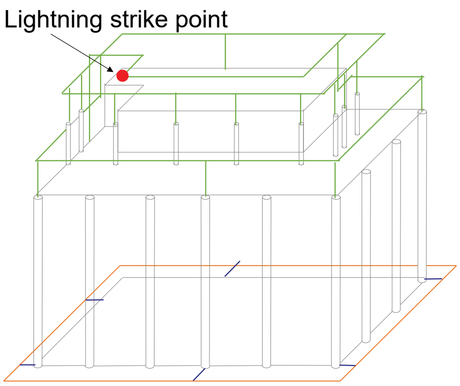


Figure 3. Calculated external lightning protection system (Building structures are used as down conductors) [25].

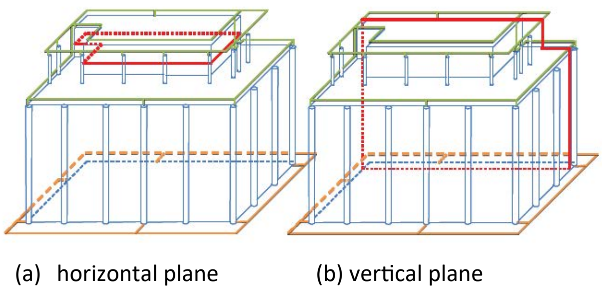


Figure 4. Calculated area of magnetic field induced by direct lightning stroke [25].

was 100kA (10/350us) of the first positive short-time lightning strike **Figure 4a and 4b**.

The analysis results are shown in **Figure 5a and 5b**. As can be seen from these results, the magnetic field is strong at the outer periphery of the building, but from the horizontal plane view of the fifth floor, it can be seen that there is a portion where the magnetic field is strong around the column inside the building, and from the vertical plane view, the magnetic field is induced in the EPS. Considering that many building electrical wiring is installed in EPS, it is feared that the whole electrical equipment used in the building would be affected by direct lightning strike.

As mentioned in chapter 2, according to JIS T1022, equipotential bonding is applied in medical facilities. Thus, since the medical grounding line is electrically connected to the reinforcing bars and the steel frame, there is a fear that lightning surges will penetrate into the medical grounding line in case of direct lightning strike. An overvoltage may occur between the enclosure of the ME equipment and the internal wiring, resulting in a flashover or failure inside the ME equipment. Furthermore, electromagnetic fields are induced around the lightning currents flowing in the columns, and there is a concern that interference caused by electromagnetic fields may occur, such as surge voltages penetrating the ME equipment and its wiring in the vicinity. The floor near the roof of the building is more susceptible to lightning strikes.

SPDs (Surge protective device) are generally used to protect against failure of ME equipment caused by overvoltage in case of lightning strikes. However, it should also be noted that SPD does not provide sufficient countermeasures in the meaning of stable operation of electrical and electronic equipment, since SPD is intended not to avoid malfunction of electrical and electronic equipment but to avoid permanent failure of them.

Countermeasure design in lightning protection system

Figure 6 shows an example of countermeasure design in lightning protection system. Air-termination system and down conductors are electrically insulated from the building structure, (i.e. isolated lightning protection system), to suppress interference between the lightning protection system and medical grounding system. That is to say, electrical independence between lightning protection system and medical grounding system is ensured.

Separation distance between air-termination conductors and the roof surface should be ensured, so that the flash-over between them and intrusion of magnetic field under the roof suppressed. For vertical medical grounding lines, use building structures, or use exclusive grounding lines. The grounding line of each floor is connected with a structure or the vertical exclusive grounding line, but the structure close to the outer wall shall be avoided because a lot of lightning current flows in the outer columns. In the figure, the medical grounding line was exclusively used. The basic principle of medical grounding electrodes is to use a structure. However, when no structure foundation is adopted, mesh grounding shall be adopted as a dedicated medical grounding electrodes as shown in the figure to reduce grounding impedance.

Analysis results when using the isolated lightning protection system of **Figure 7** are shown. The analytical model is the same as previously described. From the analysis result of **Figure 8**, it can be seen that the induction of the magnetic field around the column on the fifth floor and the magnetic field of EPS is suppressed.

Incidentally, in the case of isolated lightning protection system, it is important to insulate the air-termination system and down conductor system from the building structure. Therefore, when selecting a support material, it is necessary to select a material having a sufficient withstand voltage. If it is possible to insulate the building structure itself using fiber-reinforced plastic

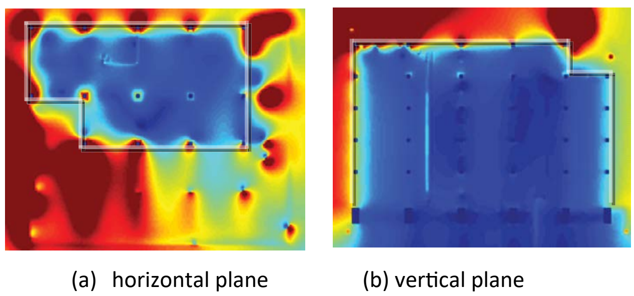


Figure 5. Calculated magnetic field distribution (A/m) (In case building structure is used as down conductors) [25].

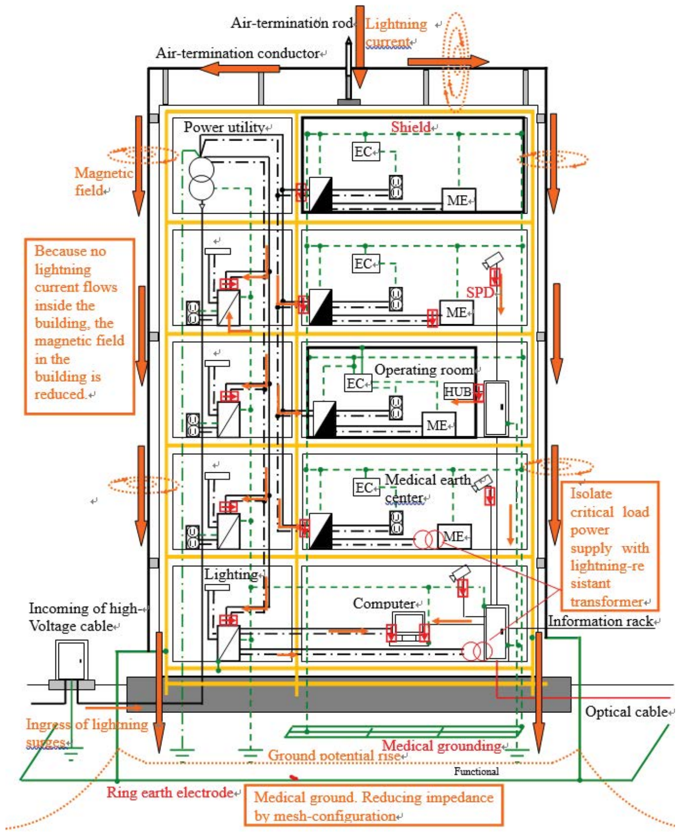


Figure 6. Example of proposal lightning protection system [19].

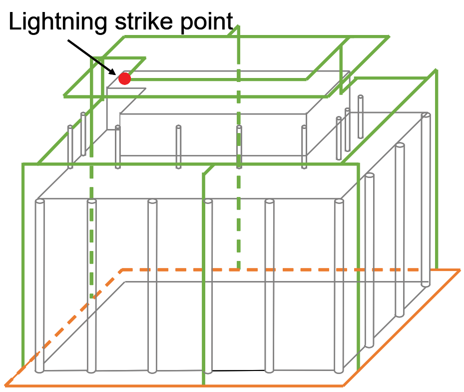
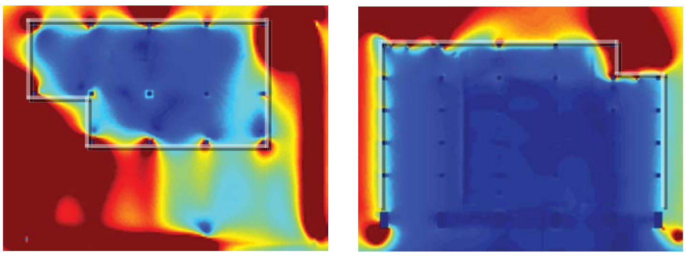


Figure 7. Calculated external lightning protection system (In case external LPS isolated from building structure) [25].



(a) horizontal plane (b) vertical plane

Figure 8. Calculated magnetic field distribution (A/m) (In case external LPS isolated from building structure) [25].

bars (aramid rebar, etc.) for the building structure, it will be easier to provide electrical insulation between the structure and the lightning protection system, but at present, fiber-reinforced plastic bars have not become a building-designated material, so problems still remain in their adoption. Figure 9 shows a photograph of an aramid rebar [27].

Figure 9. Aramid fiber rod [27].

Grounding system

Common-mode noise caused by inverters: In recent years, the availability of inverter equipment has been increasing from the viewpoint of energy saving. It is well known that common-mode noise flows from inverter equipment to grounding system of the building and causes a failure to electrical equipment [28-30].

Figure 10 shows propagation routes of the common-mode noise (high frequency leakage current) from an inverter in a building. The source of noise is an inverter panel installed on the third floor in this figure. The solid arrow in the figure represents the high-frequency leakage current, and the dashed arrow represents the induced current caused by interference with the leakage current. The leakage current flows from the inverter in the panel through the power lines to the motor, and finally to the ground via stray capacity of the motor. Unless the motor is insulated from the steel building frame, the noise finds its way back to the inverter panel through the building frame, the ground and the grounding electrodes indicated as EB and ED. The EB is called Class B grounding and is used to ground the neutral point or one wire of the low-voltage circuit. The ED is called Class D grounding and is the enclosure grounding of low-voltage equipment. Now, the noise flowing through the EB comes from the grounding wire to the receiving and transforming equipment. Then, it returns to the input side of the inverter panel on the third floor. Noise flowing through the ED returns to the ground terminal of the inverter. In medical facilities, for equipotential bonding, ME equipment shall be connected with the building structure, it may cause the leakage current to penetrate into ME equipment.

Noise induced by electromagnetic induction is induced in the wiring laid in parallel with the noise path as shown in dotted line in the figure. In addition, in the figure, $\triangle$V is expressed near the grounding electrodes, which indicates the potential rise of the grounding electrodes. The potential rise due to noise can also cause potential interference to equipment sharing a grounding electrode. So, if ME equipment requires a reference potential, the potential interference will be harm the stable operation of the ME equipment.

In the figure, the inverter board is represented as a single unit, but there are actually many inverter equipment that serve as noise sources, which are more complicated than the route of the noise, further increasing the possibility of impact ME equipment. Also, when a problem occurs, it becomes difficult to identify the cause.

Figures 11a and 11b represent actual measurement waveforms of the high-frequency leakage current generated from the inverters [31]. **Figure 11a** represents waveforms of current flowing in the grounding line of an inverter, which drive a pump. It can be seen that the leakage current is generated at the timing of switching of the inverter. **Figure 11b** shows the leakage current of Class B grounding of the power transformer supplying power to the inverter

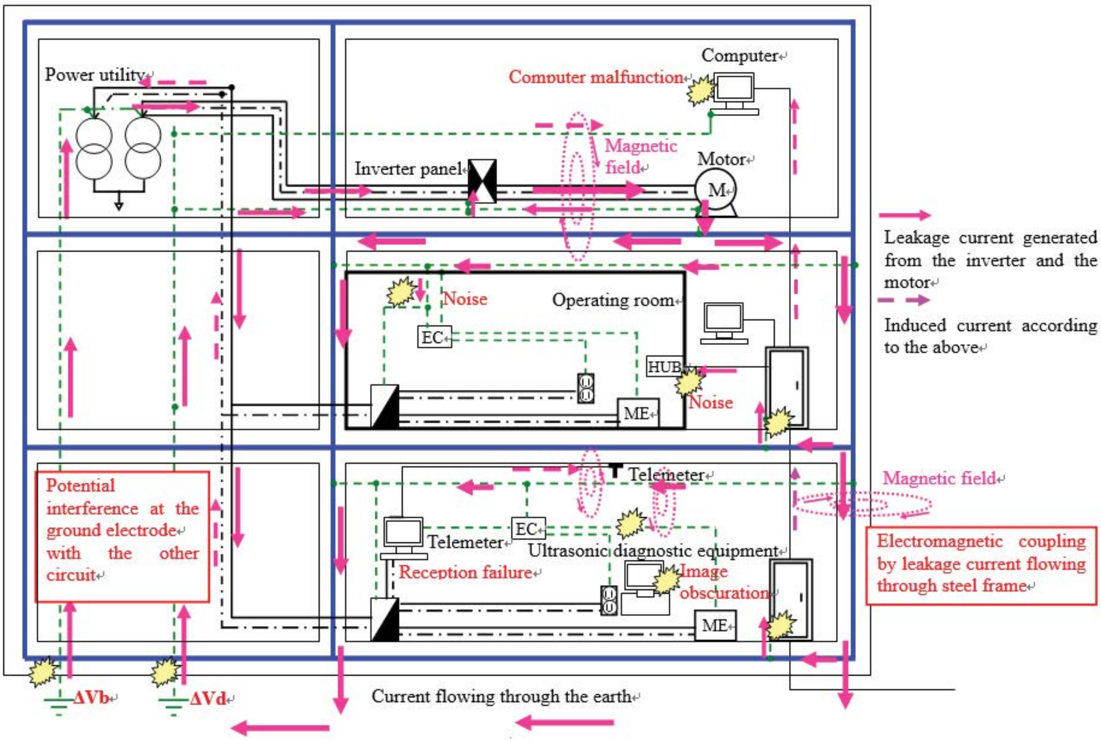
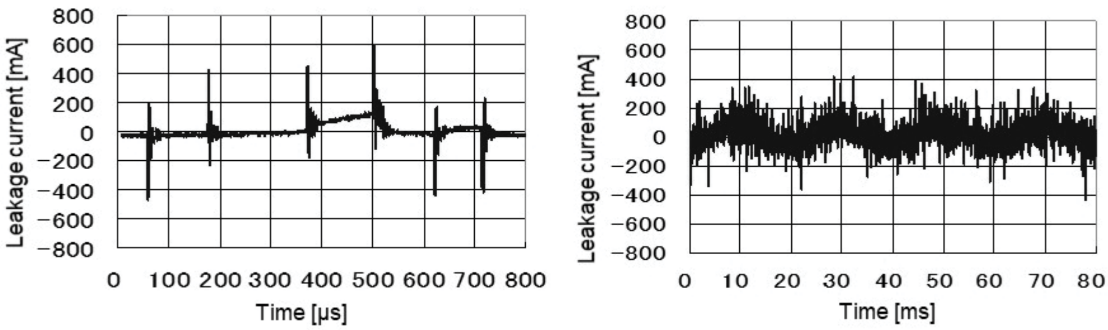


Figure 10. Route of common-mode noise (high-frequency leakage current) in a building [19].



(a) Grounding wire of an inverter (b) Class B grounding wire of a transformer

Figure 11 Measured waveforms of ground leakage current with inverter-driven loads [31].

and the pump concerned. We can see that high-frequency leakage current flows in the Class B grounding.

Countermeasure design in grounding system

Figure 12 shows an example of grounding system to suppress the impact of high-frequency leakage current. In the figure, in order to clarify the intention, the insulation between the building structure and the electrical equipment is realized by using fiber reinforced plastic bars instead of the iron reinforcing bar. In the case of iron reinforced concrete buildings, the same effect can be obtained if ME equipment, inverter boards and motors are insulated from the building structure. The vertical medical grounding lines are exclusively installed here. But if insulation measures are taken to prevent noise from entering the structure, columns may be used as a medical grounding line.

By insulating the noise source from the structure, the noise does not flow into the structure, and can be limited to flow the grounding line. Then, we can suppress intrusion of common-mode noise and radiation of electromagnetic field to the ME equipment. Although there is a path flowing through the grounding electrodes EB and ED from the grounding conductor, noise flowing through the grounding conductor can be suppressed by installing a noise filter for the grounding conductor [31] as shown in the figure.

Figure 13 shows a photograph of the noise filter, and **Figures 14a and 14b** show the measurement results of the leakage current flowing through grounding conductors after installation of the noise filters. These waveforms are measured results after installation of the noise filters to the same measured point as shown in **Figures 11a and 11b**. By comparing with **Figures11 and 14**, it can be seen that, by using the noise filter, the high-frequency current flowing in grounding line are suppressed effectively, and it is possible to create a clean grounding system in the building. Incidentally, this filter suppresses the high-frequency current, in which the current of the commercial frequency is safely passed. Therefore, the leakage current of the commercial frequency is flowing in **Figure 14b**. In addition, the proposing grounding system has the advantage that the noise propagation route can be easily identified and noise countermeasures can be easily implemented even if noise-induced disturbances occur.

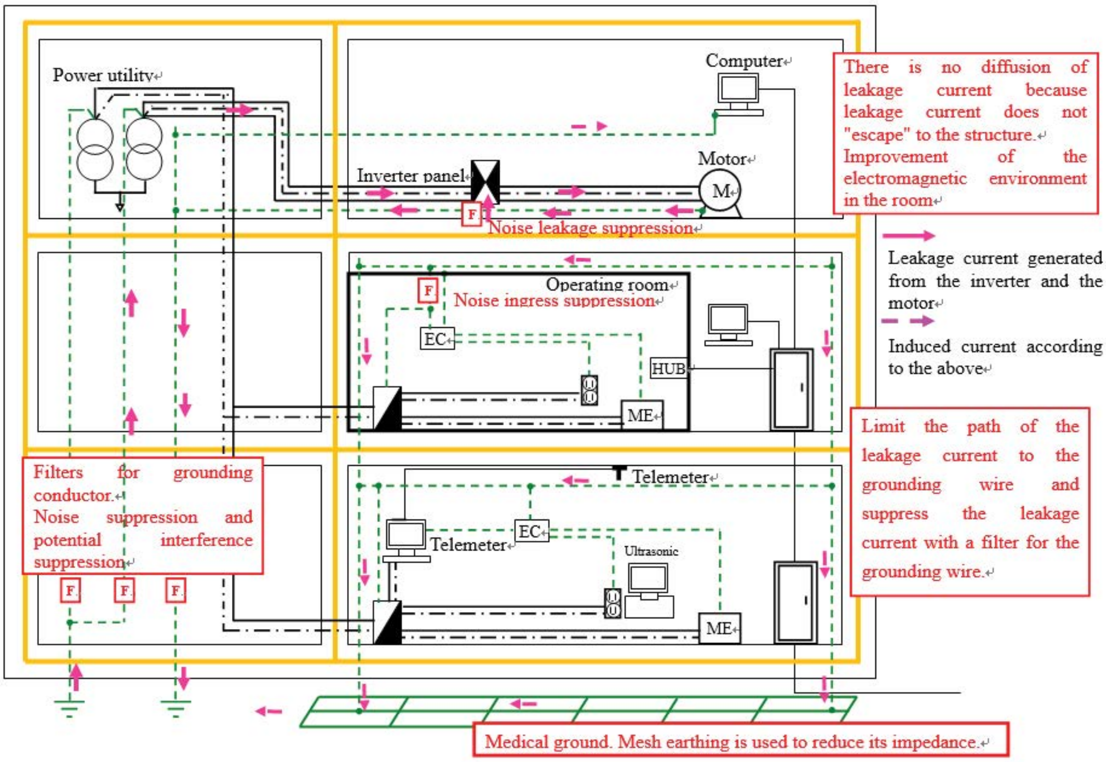
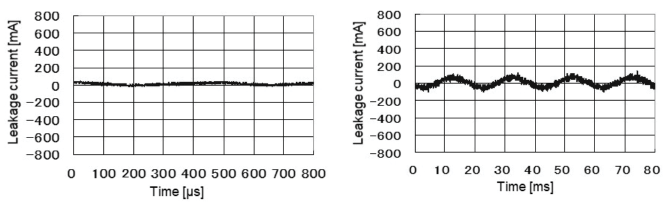


Figure 12. Example designing of measures of inverter-noise [19].

Figure 13. Noise filters for grounding system [31].



(a) Grounding wire of an inverter

(b) Class B grounding wire of a transformer

Figure 14 Measured waveforms of ground leakage current with inverter-driven loads after installation of noise filters [31].

Summary

In this paper, the electromagnetic environment guidelines in advanced electronic medical facilities were explained referring to the related preceding study and actual measurement examples. In medical facilities, failure of ME equipment directly leads to human life. The development of robot technology and IoT technology is remarkable. However, even new technologies, that enhance the level of quality and convenience, are not socially acceptable unless they are safely utilized. Therefore, utilizing these new technologies safely in medical facilities, it is necessary to examine the electromagnetic environment as a whole system, not only those ME equipment but also buildings and electrical facilities. It would be great if this paper could provide opportunities and suggestions for considering such viewpoints.

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