Simulation Study on Radiation Exposure of Emergency Medical Responders From Radioactively Contaminated Patients

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Abstract

Emergency medical responders (EMRs), who save victims in a radiation emergency, are at risk of radiation exposure. In this study, the exposure dose to EMRs assisting contaminated patients was estimated using a Monte Carlo simulation, and will produce data that contributes to EMR education and anxiety reduction. Using the Monte Carlo simulation, we estimated radiation doses for adult computational phantoms with radioactive contamination conditions radiation dosages were based on findings from previous studies. At the contamination condition corresponding to the typical upper limit of general GM survey meters, the radiation doses of EMRs were estimated to be less than μSv per hour. In case of a heavier contamination due to mishandling of an intense radioactive source with hundreds of GBq or more, their radiation doses would be close to 100 mSv per hour. The results have implied that the radiological accident with a highly radioactive source would expose EMR to the risk of significant radiation exposure exceeding the dose limit. It is thus crucial that the authority or other party who are responsible for the health of EMRs ensures that they shall have necessary education and training on the effective measures for protecting themselves from the possible, excessive radiation exposure.

Introduction

Radiation is widely used in medical and industrial fields, when nuclear or radiological accidents occur, workers of the nuclear facility and neighboring residents may be exposed to contamination with radioactive substances. An example is the Fukushima Daiichi Nuclear Power Plant (FDNPP) accident, a well-known nuclear disaster ranked at the highest level, seven, in the International Nuclear Event Scale (INES).[1−3] In the FDNPP accident, over 170,000 residents were forced to evacuate and emergency medical responders (EMRs) and health physicists required to perform difficult tasks.[2] In addition to nuclear emergencies, there have been cases of contamination and exposure of unspecified large numbers of people owing to the theft of radiation sources, such as the Goiânia accident in Brazil and the Juarez accident in Mexico.[4,5] The medical response to such radiation emergencies requires establishing international standards for training EMRs and providing them with appropriate radiological protection equipment.[6,7] The exposure doses and contamination levels of patients are estimated using various analyses. Based on these results, treatment strategies and future risks can be determined.[8,9] However, there is little discussion regarding the exposure dose that EMRs, when managing a radiation emergency, receive from their patient's radioactive contamination. For example, contamination inspections are required to comply with the International Atomic Energy Agency (IAEA) technical documents.[10] It is also possible that a highly radioactive source may be powdered and may adhere to patients, as observed in the Goiânia accident. Thus, EMRs are inevitably exposed to radioactive substances from workers and evacuees contaminated during a nuclear disaster. In addition, medical doctors and nurses who provide radiation emergency medicine are at a particularly high risk of radiation exposure. The most recent report discussing survey results of various dispatched EMRs during the FDNPP accident revealed that they were afraid of being exposed to radiation when they provided emergency care.[11] As mentioned above, EMRs are expected to have some anxiety during radiation emergencies, which may hinder their decision making despite response and personnel strategies developed as emergency responses. If it is possible to develop a standard exposure dose for EMRs, specialized education can be developed for EMRs to manage their safety and anxiety, improving their ability to respond to situations involving radiation exposure calmly. In this study, we simulate the exposure dose for EMRs who provide emergency medicine for individuals contaminated with radioactive substances based on information from past radiation emergencies. Specifically, we show the results of estimating the exposure dose of EMRs using Particle and the Heavy Ion Transport code System (PHITS),[12–14] which can calculate photon transport by assuming several radiation emergencies and contaminated patients.

Methods

Monte Carlo code used to simulate effective dose

The Monte Carlo simulation program PHITS was used to calculate the exposure dose that EMRs received from contaminated patients.[12–14] PHITS can simulate radiation behavior and has been used in various research projects in medical physics and space engineering.[15–17] Regarding photon simulation, a benchmark study has been published for energy ranging from 1 keV to 10 GeV.[14] This PHITS code was used for all physical simulations performed in the current study.

Creating simulation geometry for contaminated patient and EMR

In this study, an adult computational phantom was created in a virtual space for both a contaminated patient and a medical responder.[18] Fig. 1 shows the actual geometry image created using the PHITS code. Assuming that the contaminated patient was on a stretcher, the trunk center was placed 1 m above the ground and at a right angle to the EMR. We established the adhesion of any radioactive substance in the upper arm and abdominal cavity of the contaminated patient and the survival of the medical radiation source in the body. We calculated the photon scattering from radioactive contamination and the absorbed dose of each organ of the EMR. Finally, the effective dose was estimated by integration of the absorbed doses of organs and tissues. In this simulation, it was assumed that there was no scattering from the floor and walls.

Setting patient contamination and EMR exposure scenarios

In simulation research of emergency medicine and radiation physics, it is very important to consider the assumptions structurally. In this study, information from past radiation emergencies was used to develop two scenarios, namely one for exposure from environmentally released radionuclides and another for exposure from directly handling a radioactive source. The effective dose of an EMR was calculated. The simulation assumptions are summarized in Table 1.

Table 1
Assumption of attached radionuclides of contaminated patient in this study.

Scenario	Situations where responders are expected to be exposed	Radionuclide	Assumption of contamination density in this study	Shape of contamination	Past cases
1	**Exposure from environmentally released radionuclides** •Radionuclides released from nuclear power plants •External contaminatio of evacuees	^{131}I	**Assuming 400 Bq/cm^2 contamination on body surface** (This level is about 100,000 cpm using a GM survey meter with a window area of 20 cm^2, which is used at the time of contamination inspection of evacuees.)	Suppose there is circular contamination with a radius of 5 cm on the back of the hand.	Chernobyl nuclear power plant accident (USSR, 1986) Fukushima Daiichi nuclear power plant accident (Japan, 2011)
		^{134}Cs			
		^{137}Cs			
2	**Exposure from directly handling a radioactive source** •Illegal handling of a source without proper protection •Misuse of a source in industry/medicine	^{60}Co	**Assuming 10 GBq source on body surface**	Suppose there is point-source-like contamination on the back of the hand with a radius of 1.25 cm.	Goiânia accident (Brazil, 1987)
		^{137}Cs			Juarez accident (Mexico, 1983)
		^{241}Am	**Assuming 185 GBq contamination**	Suppose there is circular contamination with a radius of 5 cm on the back of the hand.	Hanford accident (USA, 1976)
		^{192}Ir	**Assuming 137 GBq source in body**	Assume that φ1 mm × 5 mm radiation source remains in the abdomen.	Indiana accident (USA, 1992)

In nuclear disasters such as the Chernobyl nuclear power plant (ChNPP) accident and the FDNPP accident, environmentally released radioactive substances, such as iodine and cesium, would contaminate the members of the public. This situation is simulated in Scenario 1 to show how health physicists may be exposed when they inspect contaminated residents. The contamination level was set so that the patients must be decontaminated following the Operational Interventional Level 4 (OIL4) shown in the IAEA technical document.[10] Please see Scenario 1 in Table 1 for contamination concentration and shape.

Scenario 2 reproduces body surface contamination with radioactive materials caused by the theft or mishandling of medical or industrial sources, as occurred in the Goiânia accident, the Juarez accident, the Hanford accident, and the Indiana accident. In addition, the assumption of the amount of contamination in Scenario 2 is based on documenting information[19,20] and the radioactivity of radiation sources used for medical or industrial use. Please note that it is not a faithful reproduction of past radiological accident cases. Detailed information such as the size and area of contamination is shown in Table 1, arranged by testing scenario.

Verification of simulation accuracy

As shown in Sato, et al., [13] various benchmarks have been verified for radiation and energy that PHITS can handle. In a physical simulation study, it is indispensable to confirm the deviation from the actual measurement; thus, our research group prepared phantoms and the other conditions in the reproducible range and attempted accuracy verification. We placed a human phantom (PBU-60, Kyoto Giken Kogyo Co., Japan) on a stretcher and attached a ^{60}Co-sealed radiation source (57,200 Bq as of the measurement date) to the upper arm of the phantom. The absorbed dose in the air was then measured using a 3-in × 3-in NaI(Tl) scintillation spectrometer (EMF-211, EMF Japan Co., Japan) at points equidistant from the contamination site. Specifically, the spectrometer was set at 10-cm intervals from 10 cm to 100 cm away from the contaminated area. The absorbed dose in the air was measured three times with a measurement time of 5 minutes each. Similarly, at a distance of 10 cm from the contaminated site, the spectrometer was installed at 40 cm, 70 cm, 100 cm, 130 cm, and 160 cm from the floor, and five data readings were acquired. The same geometry and cobalt radiation source, as in these actual measurement experiments, were used with PHITS. The accuracy was verified by comparing the measured values with the simulation model. In the results section, we first show the accuracy verification results, followed by the other simulation findings.

Results

Accuracy verification of built simulation model

The actual measurement results and simulation results are shown in Fig. 2. Comparing the measured values and simulated values, when the spectrometer was set at 10-cm intervals from 10 cm to 100 cm away from the contaminated site, the relative error rate was within 14% at all points (Fig. 2A). Similarly, the relative error rate with the simulated value was within 14% when compared with results measured by changing the height of the spectrometer at a distance of 10 cm from the contaminated site (Fig. 2B). At each point, the simulated values of the absorbed dose in the air did not underestimate the measured values. After confirming that they were accurate enough to conduct the research, the simulations shown in the following sections were performed.

Expected exposure dose of EMRs dealing with contaminated patients in nuclear emergencies and radiological accidents

Figures 3 and 4 show the simulation results. First, when dealing with injured persons or evacuees with contamination at the upper limits of a general GM survey meter, the maximum external exposure dose of an EMR is approximately 33 nSv per hour at a distance of 10 cm from the contamination (Fig. 3). Next, we determined that when dealing with a victim who may have been contaminated with a powder from the radiation source, the external exposure dose of an EMR is approximately 16 mSv per hour (Fig. 4A). When the scenario focuses on injured persons contaminated by residual large-capacity radiation sources, such as therapeutic radiation sources, the maximum external exposure dose of an EMR is approximately 48 mSv per hour (Fig. 4B). In addition, assuming contamination with ^{241}Am of several hundred GBq, as occurred in the Hanford accident, it was determined that the maximum external exposure dose of an EMR was approximately 12 mSv per hour (Fig. 4C).

Expected time to reach various dose limits

Based on our simulation results, Table 2 summarizes the estimated time to reach the dose limit during planned or emergency exposure presented in ICRP Pub 103.[21] Fig. 5 provides a quick view of the exposure dose of an EMR when providing medical care at a distance of 10 cm from the contaminated site in Scenario 2, which simulates theft or handling error of a medical or industrial radiation source. IAEA recommends that the average planned occupational exposure dose limit over five years should be 20 mSv per year or less, and that it should not exceed 50 mSv per year in any year. Under emergency exposure situations, the exposure dose limits of 100, 500, and 1000 mSv are presented as a reference. Therefore, based on simulation results obtained in the two scenarios shown in Table 1, the expected time to reach exposure dose limits of 1, 20, 50, or 100 mSv from medical treatment at a distance of 10 cm from the patient (contaminated site) was calculated.

Table 2
Expected time to reach various dose limits.

Scenario a)	Radionuclides	Expected time to reach dose limits			
		1 mSv	20 mSv	50 mSv	100 mSv
2	^{60}Co	3.76 min	1.24 h	3.13 h	6.27 h
	^{137}Cs	15.25 min	5.11 h	12.79 h	25.58 h
	^{241}Am	4.73 min	1.57 h	3.94 h	7.88 h
	^{192}Ir	1.25 min	25.06 min	1.04 h	2.09 h

a) The meaning of the scenario is shown in Table 1. The expected times were derived from the dose rates at a distance of 10 cm from the patient.

We found that when an EMR responds to workers and evacuees with contamination exceeding OIL4, which is expected in a nuclear disaster, the expected time to reach 1 mSv would be longer than 1000 hours. If contamination with an amount of radioactivity expected under Scenario 2, such as theft or mishandling of a radiation source of tens to hundreds of GBq, it was expected that an exposure dose of 1 mSv would be reached in a period ranging from a few minutes to tens of minutes of exposure. With ^{192}Ir, the simulation result showed that if EMRs provide medical treatment at a distance of 10 cm from a contaminated patient for approximately 2 hours, an EMR would be exposed to about 100 mSv.

Discussion

According to the principle of optimization, known as "As Low As Reasonably Achievable (ALARA), that efforts should be made to reduce the exposure dose of the public and professionals as much as possible.[21–23] This ALARA principle also applies in radiation emergencies. However, in the event of a radiation emergency, when an EMR responds to an exposed and/or contaminated patient, saving the life of the patient being the priority and the determination of the treatment strategy, including an exposure dose evaluation, is important.[24,25] The management of the exposure dose of professionals, such as EMRs, makes it difficult to achieve the ALARA principle because of the priority placed on saving patients' lives. It is conceivable that an emergency medical doctor, nurse, and health physicist will encounter situations where they will deal directly with contaminated victims and evacuees. In those situations, it would be difficult to secure sufficient distance and time for unknown contamination. EMRs wear a personal dosimeter to measure the exposure dose and wear protective clothing to prevent contamination. However, these measures cannot predict the exposure dose in an emergency. To provide emergency radiation medicine, it is very important to predict and manage the exposure dose of EMRs. Protocol and planning need this information for strategy planning, which would include replacement personnel requirements and permitted activity time.[26]

The results of this simulation study were obtained using the PHITS code for which benchmarks have already been established. When compared with the actual measurement experiments, the simulation values were comparable and did not underestimate actual values. The relative error rate was within 14% overall, a sufficiently reliable value (Fig. 2). Based on the simulation results of this study, when EMRs respond to victims with contamination exceeding OIL4, it was found that the exposure dose of an EMR did not approach the dose limit when considering the actual activity time (Fig. 3, Table 2). In the case of contaminated injuries caused by theft of or accidents involving radiation sources for medical and industrial applications, it was shown that an EMR might suffer exposure ranging from 1 mSv to 100 mSv (Fig. 4, Table 2). The exposure dose of an EMR who provides radiation emergency medicine is the exposure dose when the contaminated area of the victim is not decontaminated at all. It is necessary to keep in mind that the exposure dose of both the patient and EMR can be reduced by performing appropriate decontamination after the patient's lifesaving measures are taken. Accidents in which a high-radioactivity source is attached to a patient are rare. It is unlikely that exposure to EMR by radioactive substances attached to the patient will cause a deterministic effect. Still, it is important to control the exposure dose for radiological protection.

Several studies emphasize the anxiety related to radiation among medical professionals and the importance of radiological protection education. For example, Sato et al. conducted a questionnaire survey of nurses working at core hospitals in Fukushima Prefecture after the FDNPP accident and revealed that many nurses were considering retirement or migration owing to radiation anxiety and radiation-related health effects.[27] Akashi et al. advocated the significance of promptly providing radiological protection information to the Disaster Medical Assistance Teams.[28] As reported in these previous studies, it is important to provide radiological protection and radiation emergency medical education for EMRs. The guidelines published by the IAEA in 2020 show the importance of obtaining the cooperation of medical physicists with experience in radiation emergencies.[29] Research data show that improving the activity capacity of EMRs and reducing their anxiety is critically important in radiological protection.

The results shown in Figs. 4 and 5 can be a quick reference data of EMRs' exposure doses, assuming several scenarios involving medical and industrial radiation sources. Such an event is rare, but they have occurred, as shown by the Brazilian Goiânia accident and the American Indiana accident. There are only two accidents with radiation measured at the highest level 7 in INES: the ChNPP accident and the FDNPP accident. Still, the overall number of radiological accidents is more than 600 in the 30 years. Over 2000 incidents have been reported with exposed/contaminated victims.[30, 31] In addition to these, the existence of additional threats, such as nuclear terrorism, further shows the importance of radiological protection for EMRs.

Although rare events, once a radiological accident or nuclear disaster occurs, societal anxiety and impact would be enormous. Radiological protection and education before the occurrence of these emergencies are important for EMRs and institutions that will handle radiation emergencies. The research results in this paper will be useful for the education of EMRs. We try to achieve it in our educational work.

Declarations

Author contributions:

TT contributed to the construction of simulation models, accuracy verification experiments, all reference searches and manuscript writing; YS, MS, and KN contributed to the construction of simulation model; KI, HY, ST, and IK advised on setting simulation conditions, organizing data, and performing accuracy verification experiments.

Competing interests

The authors declare no competing interests.

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Figures

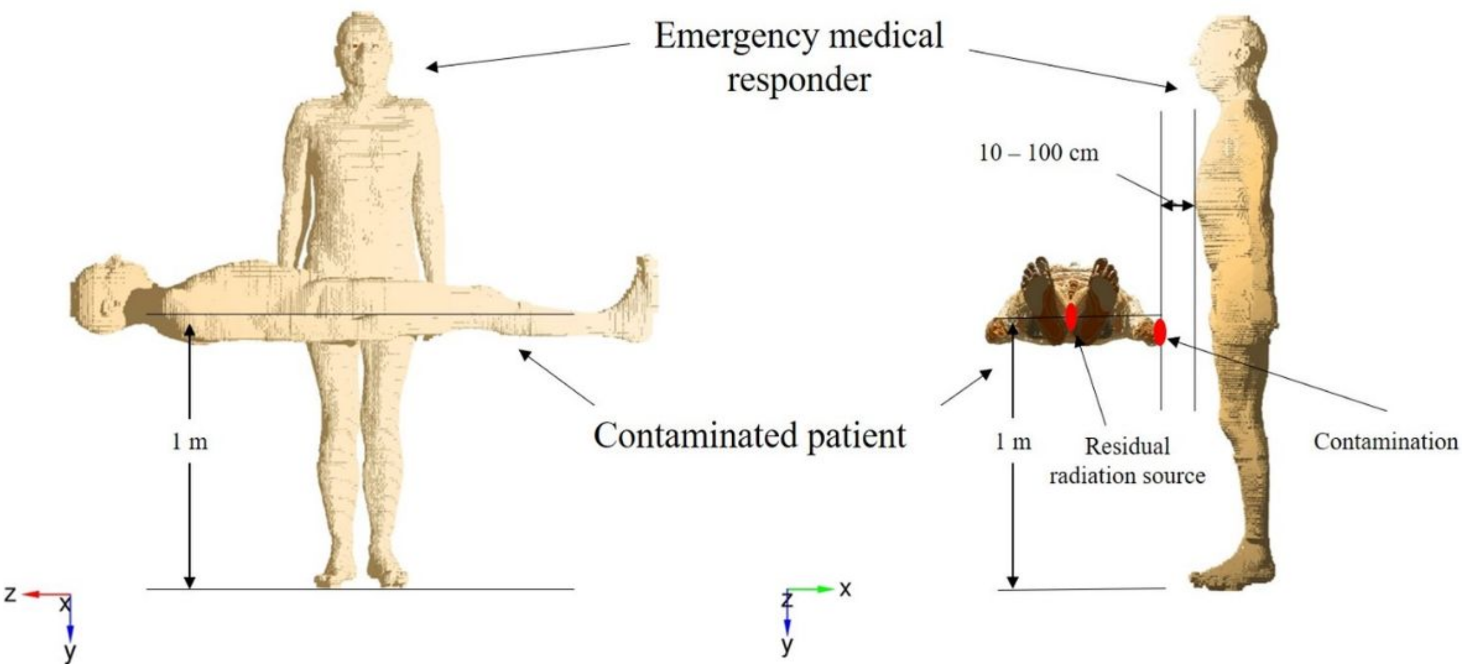

Figure 1

Geometry created using PHITS. The radionuclides can be set to any location, and the amount of contamination and the distance between the patient and EMR can be changed arbitrarily.

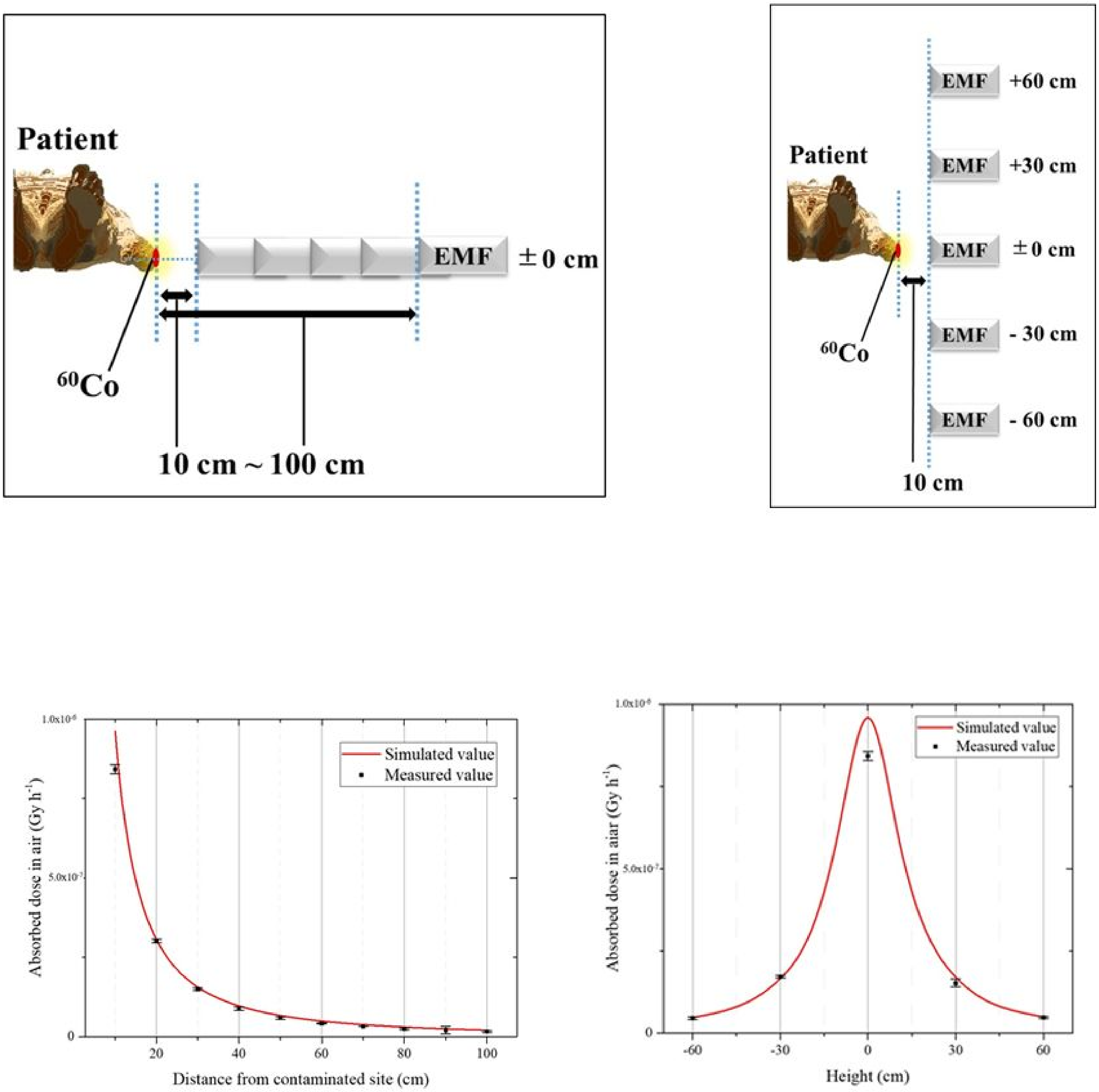

Figure 2

The result of the accuracy verification of the constructed simulation model. (A) Outline when the spectrometer was set at 10-cm intervals from 10 cm to 100 cm away from the contaminated site. (B) Outline when the height of the spectrometer was changed to a distance of 10 cm from the contaminated site. (C) Comparing the measured values and simulated values when the spectrometer was set at 10-cm intervals from 10 cm to 100 cm away from the contaminated site and (D) when the height of the spectrometer was changed to a distance of 10 cm from the contaminated site.

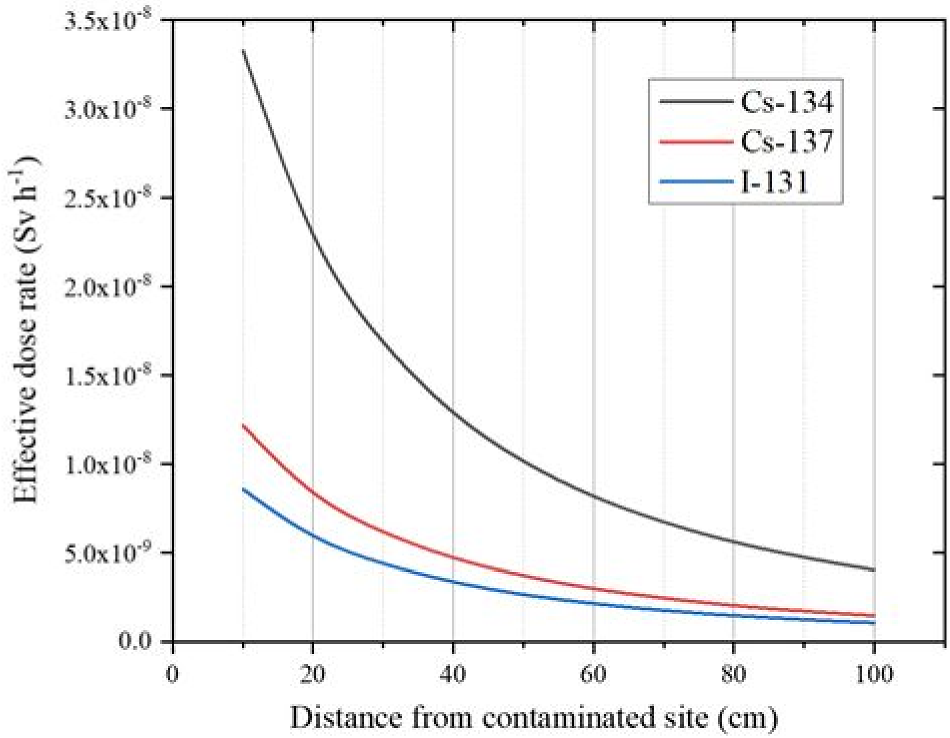

Figure 3

Exposure doses of EMR who cares a patient contaminated with radionuclides that are expected to be released during a nuclear disaster. Each of the three sources is on the surface of the body and has an intensity of 400 Bq cm-2. See scenario 1 in Table 1 for detailed settings such as contamination levels.

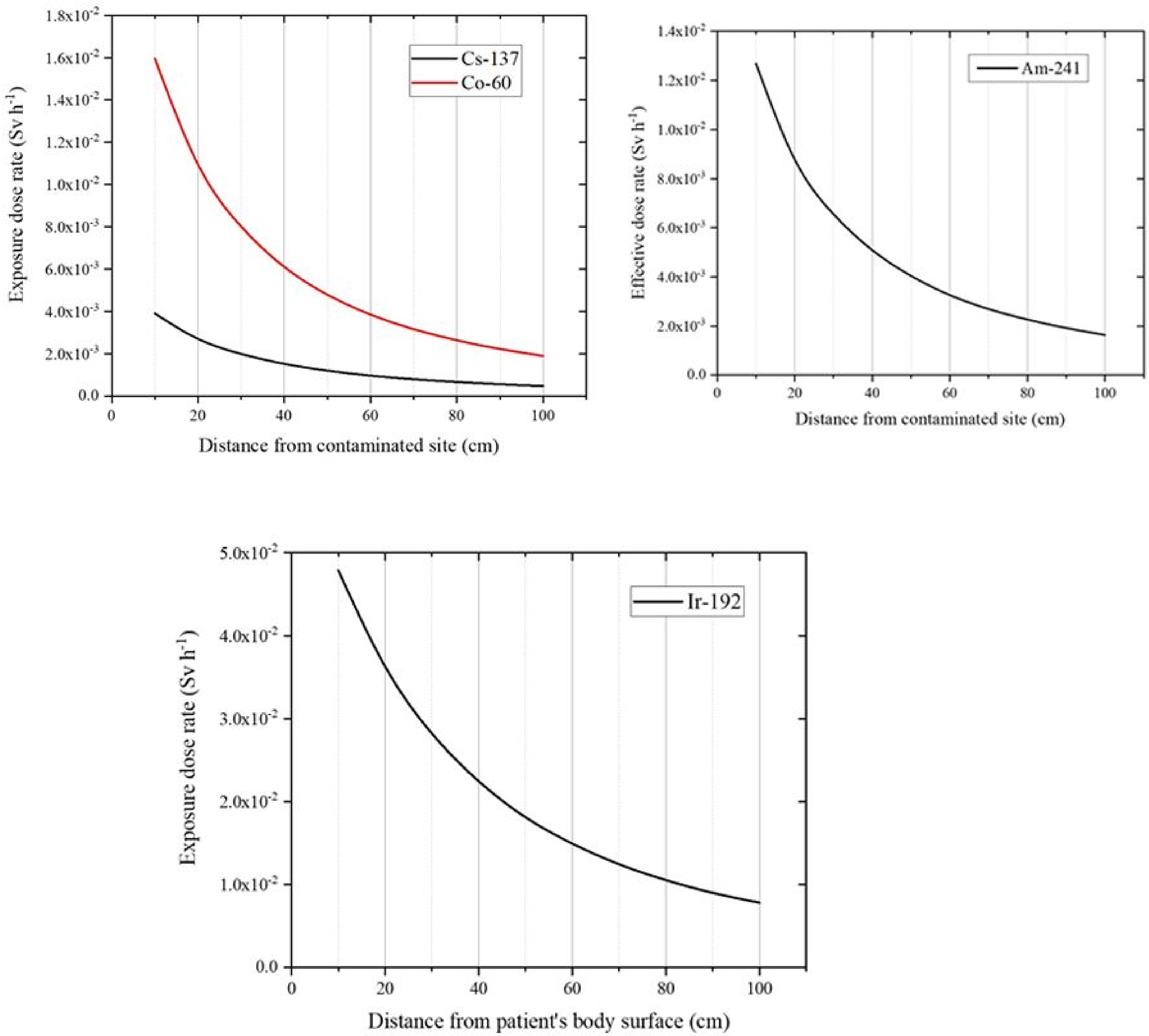

Figure 4

Exposure dose of EMR who cares a patient with highly radioactive contamination during a radiological accident. See Scenario 2 in Table 1 for detailed assumptions for each. (A) Radiological accidents associated with the theft of medical/industrial radiation sources. The intensity of the source is 10 GBq. (B) Radiological accident caused by mishandling of industrial radiation source. The intensity of the source is 185 GBq. (C) Radiological accident owing to mishandling of medical radiation sources such as brachytherapy. The intensity of the source is 137 GBq.

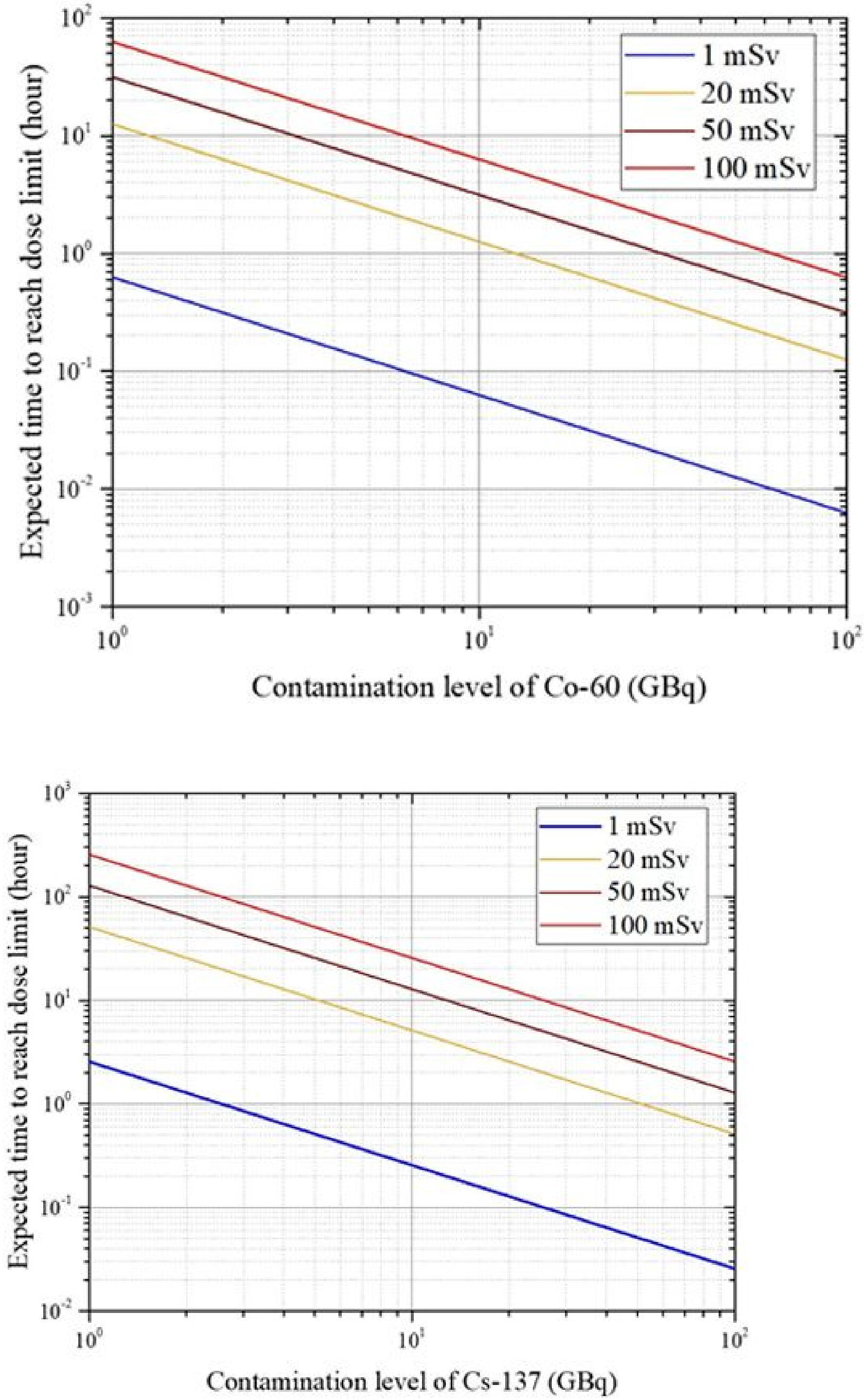

Figure 5

Results showing the exposure dose of an EMR corresponding to a patient contaminated by a highly radioactive radiation source at a distance of 10 cm for each contamination amount. When the contaminated nuclide is (A) 60Co or (B) 137Cs. Contamination is assumed to be within a radius of 1.25 cm on the back of the hand. Same conditions as cobalt and cesium in Scenario 2 in Table 1.