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Identification of penetration path and deposition distribution of radionuclides in houses by experiments and numerical model

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ABSTRACT

In order to lift of an evacuation order in evacuation areas and return residents to their homes, human dose assessments are required. However, it is difficult to exactly assess indoor external dose rate because the indoor distribution and infiltration pathways of radionuclides are unclear. This paper describes indoor and outdoor dose rates measured in eight houses in the difficult-to-return area in Fukushima Prefecture and identifies the distribution and main infiltration pathway of radionuclides in houses. In addition, it describes dose rates calculated with a Monte Carlo photon transport code to aid a thorough understanding of the measurements. The measurements and calculations indicate that radionuclides mainly infiltrate through visible openings such as vents, windows, and doors, and then deposit near these visible openings; however, they hardly infiltrate through sockets and air conditioning outlets. The measurements on rough surfaces such as bookshelves implies that radionuclides discharged from the Fukushima-Daiichi nuclear power plant did not deposit locally on rough surfaces.

1. Introduction

Enormous amounts of radionuclides were deposited over large areas of Japan by the Fukushima-Daiichi accident in 2011. In consequence, an evacuation order was issued for large areas of Fukushima Prefecture. The areas where the annual cumulative dose was expected to be 20–50 mSv or exceed 50 mSv were defined as the restricted residence area and the difficult-to-return area, respectively; these are areas from which people remain evacuated (IAEA, 2015). Due to recent decontamination activities, the area in which residents can return to their homes has gradually increased (Reconstruction Agency, 2016).

In order to lift of an evacuation order in both zones in preparation for the lifting of the evacuation order and restricted residence area and return residents to their homes, human dose assessments are required. In particular, indoor external dose assessment is important because residents may remain indoors for long periods. The International Atomic Energy Agency (IAEA)-TECDOC-225 (IAEA, 1979) and TECDOC-1662 (IAEA, 2000) suggested that the representative dose reduction factor of a wooden house is 0.4. However, according to measurements after the Fukushima-Daiichi accident, there were some houses where the dose reduction factor exceeded 0.4 (Yoshida-Ohuchi et al., 2014). Yoshida-Ohuchi et al. (2014) pointed out the possibility of radioactive contamination on indoor surfaces as one of the reasons for this. Furuta and Takahashi (2014, 2015) calculated indoor dose rate distributions with a Monte Carlo photon transport code to evaluate the influence of radionuclides deposited on outdoor ground. However, their calculations did not consider the influence of radionuclides on indoor surfaces. Upon a radioactive plume passing over a house, a portion of the radionuclides can infiltrate into the house through openings such as windows, doors, and vents, and can then deposit near the openings as well as on indoor surfaces. Hence, the indoor external dose should be assessed by taking into account the influence of radionuclides deposited on indoor surfaces as well as those on outdoor ground. However, the indoor external dose rate cannot be assessed accurately because the infiltration pathways and indoor distribution of radionuclides are unclear.

Therefore, this study aims to accurately assess the doses to people living in areas contaminated by the Fukushima-Daiichi accident. In this study, outdoor and indoor dose rates at the center of rooms and near openings were measured in houses in the difficult-to-return area. The indoor dose rates were calculated with a Monte Carlo photon transport code, with the following aims: (i) to investigate the difference between indoor and outdoor dose rates, (ii) to examine the indoor distribution and main infiltration pathways of radionuclides, and (iii) to explore the contribution of various contaminated surfaces to indoor dose rate

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measurements.

2. Materials and methods

2.1. Experimental methods

In October and November 2015, ambient dose equivalents (hereinafter dose rates) were measured by a NaI(Tl) scintillation survey meter (Hitachi Aloka Medical Ltd., TCS-171B) in eight houses (referred to as Houses A–G) in Futaba town and Ohkuma town, which are located in the difficult-to-return area in Fukushima Prefecture. The measurements were carried out as follows: Dose 1 was measured at a height of 1 m from ground level at the four corners outside a house, Dose 2 was measured at a height of 1 m from floor level in the center of a room, and Dose 3 was measured at a height of 5 cm from the indoor surfaces of the floor, wall, and ceiling.

To examine the indoor distribution and main infiltration pathway of radionuclides, Dose 3 was measured at the center of the floor and ceiling and on the surfaces around openings (which are defined as windows, doors, ventilations, air conditioning outlets, and sockets in this paper). It is reported that the inflow of air from such openings is large (Murakami and Yoshino, 1983). Dose 3 around the openings was measured on surfaces about 10 cm and more than 50 cm from each opening.

It is reported that the indoor deposition rate of radionuclides depends on the surface-area-to-volume ratio of a room (Fogh et al., 1997). In this study, Dose 3 was also measured on the surfaces of a bookshelf filled with books and near the bookshelf to examine the surface area dependence of the deposition amount. During the measurement of Dose 3, the detector was covered with a 1.5-cm-thick cylindrical Pb collimator to eliminate the influence of radiations from outside the target area.

2.2. Computational methods

To explore the contribution of various contaminated surfaces to the indoor dose rates, dose rates were calculated with the Monte Carlo photon transport code EGS5 (Hirayama et al., 2005). We constructed a model house of 12 m×8 m×5.5 m (Fig. 1) with a first floor and second floor. The thickness of the walls, roof, and floorboards was assumed to be 4 cm based on Furuta and Takahashi (2015). The density and elemental composition of the walls, roof, floor, and soil were based on Furuta and Takahashi (2014, 2015). Cs-137 was assumed to be distributed uniformly (=1 Bq m^{-2}) at the following locations: p(i) on the outdoor ground surface, except for under the house; p(ii) in the ground, except for under the house, with a depth profile of concentration C described by an exponential function:

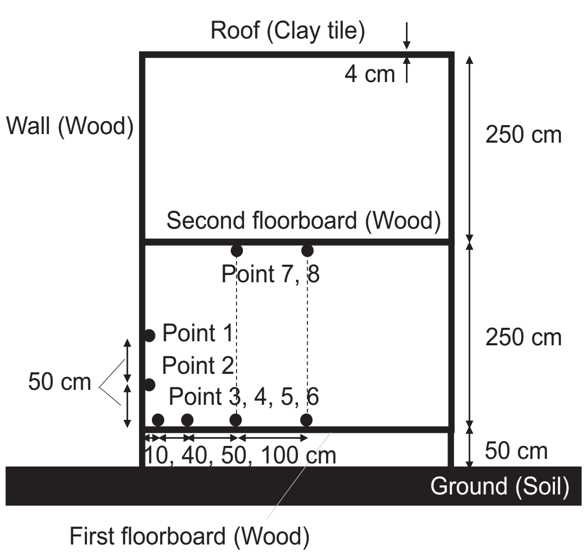

Fig. 1. Layout of the model house and dose rate evaluation points.

Table 1
Measured outdoor and indoor dose rates and the ratios of indoor to outdoor dose rate.

House	Dose rate (μSv h^{-1}) Indoor (Dose 2)	Outdoor (Dose 1)	Dose 2/ Dose 1	House	Dose rate (μSv h^{-1}) Indoor (Dose 2)	Outdoor (Dose 1)	Dose 2/ Dose 1
A	2.86	4.90	0.58	E	0.49	0.93	0.53
	3.10	4.90	0.63		0.48	1.08	0.45
	2.97	4.90	0.61		0.47	1.17	0.40
	3.49	8.35	0.42	F	1.17	5.08	0.23
	2.23	6.10	0.37		1.22	4.67	0.26
	2.25	6.10	0.37		0.92	4.67	0.20
	2.46	6.60	0.37		0.94	4.91	0.19
B	2.16	4.91	0.44		1.30	4.67	0.28
	2.59	4.91	0.53		0.95	3.14	0.30
	1.46	3.08	0.47	G	2.02	4.76	0.42
	1.82	5.08	0.36		2.10	4.76	0.44
	1.92	5.08	0.38		2.72	6.38	0.43
	1.53	4.67	0.33		2.61	6.57	0.40
	1.32	3.14	0.42		1.46	6.57	0.22
	1.52	3.14	0.48		1.50	6.57	0.23
	1.37	3.14	0.44		1.57	6.57	0.24
	2.20	3.14	0.70		1.53	3.21	0.48
C	8.31	15.48	0.54		2.03	3.21	0.63
	4.46	15.48	0.29	H	2.83	5.12	0.55
	7.79	15.29	0.51		3.60	5.93	0.61
	6.81	15.29	0.45		3.59	5.93	0.61
	6.32	15.29	0.41		3.30	6.77	0.49
	6.55	15.29	0.43		3.32	6.77	0.49
	5.44	15.65	0.35		3.52	8.31	0.42
	4.71	15.96	0.29		3.14	8.31	0.38
	4.08	11.51	0.35				
D	0.63	0.83	0.75				
	0.57	0.83	0.68				
	0.72	0.95	0.76				
	0.78	1.47	0.53				
	0.78	1.26	0.62				
	0.71	1.26	0.56				
	0.67	1.26	0.53				
	0.68	1.26	0.54				
	0.62	1.13	0.55				
	0.65	1.34	0.48				
	0.65	1.34	0.48				
	0.63	1.34	0.47				
	0.57	1.34	0.42				

$$C = C_0 \exp\left(-\frac{d}{\beta}\right),$$

where C_O is the concentration on the surface, d is depth (g cm^{-2}), and β is often called the relaxation mass depth (g cm^{-2}) and was set to 3 g cm^{-2} based on Matsuda et al. (2015); p(iii) on the outdoor wall; p(iv) on the roof; p(v) on the ground floor indoor wall; and p(vi) on the first floor floorboards. The detector was set at the measurement point shown in Fig. 1. Additionally, the Pb collimator was set to reproduce the measurements.

3. Results and discussion

3.1. Indoor and outdoor dose rates

This section reports the investigation of the difference between Doses 1 and 2 (shown in Table 1). Dose 1 was measured at the point closest to the measurement point of Dose 2. Dose 1 values differed among the houses due to differences in the deposition amount of radionuclides, and ranged from 0.83 to 15.96 μSv h^{-1}. It is apparent