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Reduction factors for wooden houses due to external γ-radiation based on in situ measurements after the Fukushima nuclear accident

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For estimation of residents' exposure dose after a nuclear accident, the reduction factor, which is the ratio of the indoor dose to the outdoor dose is essential, as most individuals spend a large portion of their time indoors. After the Fukushima nuclear accident, we evaluated the median reduction factor with an interquartile range of 0.43 (0.34–0.53) based on 522 survey results for 69 detached wooden houses in two evacuation zones, Iitate village and Odaka district. The results indicated no statistically significant difference in the median reduction factor to the representative value of 0.4 given in the International Atomic Energy Agency (IAEA)-TECDOC-225 and 1162. However, with regard to the representative range of the reduction factor, we recommend the wider range of 0.2 to 0.7 or at least 0.2 to 0.6, which covered 87.7% and 80.7% of the data, respectively, rather than 0.2 to 0.5 given in the IAEA document, which covered only 66.5% of the data. We found that the location of the room within the house and area topography, and the use of cement roof tiles had the greatest influence on the reduction factor.

The Great East Japan Earthquake of magnitude 9.0 and the tsunami on 11 March 2011 resulted in major damage to the Fukushima Daiichi nuclear power plant (FDNPP). Following plural hydrogen explosions, a large amount of radioactive material was released into the environment and moved as a radioactive plume with the wind[1–4]. On 15 March, rain began to fall and turned to sleet and snow. Due to the wind direction and the rainfall, large amounts of radionuclides were deposited northwest of the FDNPP[5]. On 12 March, the Japanese government designated the 20-km radius around the FDNPP as a restricted area, and the residents within a radius of 20 to 30 km were ordered to "stay in house". The "stay-in-house" area was changed to the "deliberate evacuation area" on 22 April[1]. By 8 August 2013, these areas to which evacuation orders were issued were rearranged into three areas responding to the annual cumulative dose, as shown in Fig. 1. Areas 1, 2 and 3 were those to which the evacuation orders were ready to be lifted, in which the residents were not permitted to live, and where it is expected that the residents will have difficulty returning for a long time, respectively[6]. Nearly 80,000 people, including 6,000 from Iitate village and 13,000 from Odaka district, are still taking refuge[6]. At present, external exposure to radionuclides which were deposited in the environment is the dominant contribution to whole-body dose to the public. To estimate the exposure dose and/or the cumulative dose properly is required for the government or the local government to determine the area to be decontaminated and is necessary for residents to plan temporary access to the area. To estimate the annual cumulative dose, the reduction factor, which is the ratio of the indoor dose to the outdoor dose, is essential, as most individuals spend a large portion of their time indoors. Shielding due to house materials and structures can reduce the dose from external penetrating gamma radiation. Most of the houses in the evacuation zone are made of wood and are one- or two-story structures. Wooden houses offer less protection than do reinforced concrete buildings due to the light outer walls. The shielding factor is sometimes used and has the same meaning and definition as the reduction factor[7]. Both factors include not only the shielding effect by house materials and structures, but also the effect from the ground right under the building, which is not contaminated by artificial radionuclides. Thus, the term reduction factor is used in this paper instead of the shielding factor.
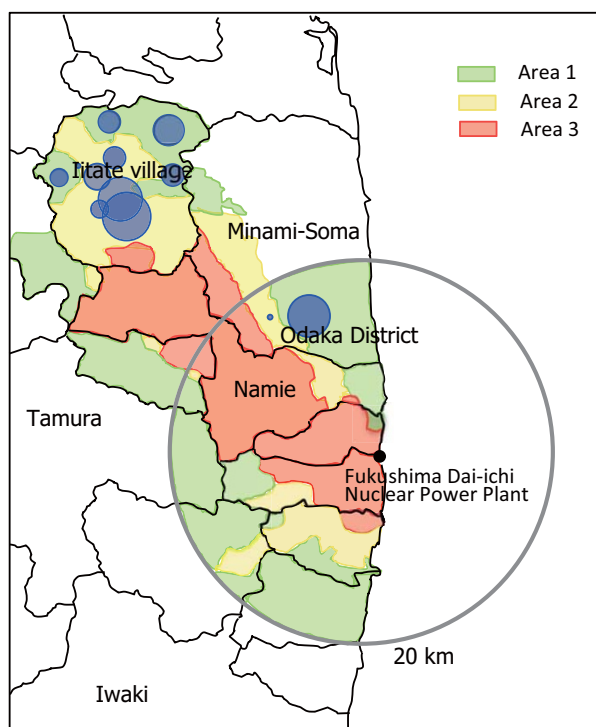
Figure 1 | Map of the measurement locations and evacuation zones. The size of the blue, closed circles depends on the number of houses investigated at each location. The map was created using Microsoft Power Point software (version 14.4.5).

The Japanese government used 0.4 as the reduction factor for one- and two-story wooden frame houses referring to the International Atomic Energy Agency (IAEA)-TECDOC-225[8] and 1162[7], in which the representative reduction (shielding) factor for surface deposition is 0.4, and the representative range is 0.2–0.5 for wooden houses. However, it is unclear whether the reduction factor and the representative range given in the IAEA document are practically appropriate.

The aim of this study is to evaluate and determine the reduction factor for Japanese single-family detached wooden houses based on in situ measurements in the evacuation zones. The results were compared with those given in the IAEA document, validating the representative reduction factor and the representative range for wooden houses.

Results

Dose rates due to natural radiation sources in the environment. The indoor and outdoor absorbed dose rate in the air due to natural radiation sources was estimated from the gamma ray energy spectra measured using an NaI (Tl) scintillation spectrometer during in situ measurements. The average outdoor dose rate due to natural radiation sources was evaluated 37.6 ± 7.6 nGy/h with one standard deviation. This value was the same level with that which was measured before the nuclear accident (30–40 nGy/h)[9] and was lower compared with that of western Japan (86.4 ± 16.1 nGy/h)[10]. The average ratio of the indoor to outdoor natural gamma-ray exposure rate was approximately 0.86 (N = 219, one standard deviation of the N ratios is 0.17 and the standard error is 0.012). The average value of 0.86 indicated no statistically significant difference to the ratio (0.7) reported in the 1977 report of UNSCEAR[11] and the ratio (0.77[12], 1.02[13]) measured in Japanese wooden houses, but lower than another report (1.42[14]). The difference between our result and the ratio (1.42[14]) might be

caused by the different methods of selecting the locations for the indoor and outdoor measurements.

Reduction factor. The relationship between the indoor and outdoor ambient dose equivalents for all of the data is shown in Fig. 2. A moderate linear relationship was observed, resulting in slope = 0.44, SE = 0.30 when the linear fit was established for the data. This was due to artificial radionuclides which were released after the FDNPP accident as no clear relationship is usually observed between the indoor and outdoor gamma-ray dose rate due to natural radiation sources in the environment[12,14].

The frequency distribution of the reduction factor for 522 results calculated using Eq. (1) is shown as bars in Fig. 3. The median reduction factor with an interquartile range was 0.43 (0.34–0.53), which is close to the value of the slope obtained in Fig. 2. The interquartile range is expressed by Q1–Q3, which are the middle value in the first half and the second half of the rank-ordered data set, respectively.

The type, the location, number of rooms where the indoor measurements were collected, and the median reduction factor with an interquartile range (Q1–Q3) are shown in Table 1. Regarding the rooms on the first floor, the arrangement of the rooms in a house was similar in all houses investigated. The living room was commonly located in the sunny front side of the house, and the bedroom was located in the back of the house.

Discussion

The result in Fig. 3 indicates no statistically significant difference in the median reduction factor to the representative value of 0.4 in the IAEA-TECDOC-225[8] and 1162[7]. The IAEA-TECDOC-1162 document gives the representative reduction (shielding) factor range of 0.2 to 0.5 for one- and two-story wooden frame homes. This range was determined by experimental results of full scale structures using a radioactive source[15,16]. The frequency reduction factor distribution measured experimentally for wooden frame houses, which is referred to as the CEX-59.13[16], is also plotted in Fig. 3 (closed squares). Comparing the reduction factor frequency distribution observed in this study and that measured experimentally, it is clear that the former (shown as bars) tends toward a larger reduction factor value. It is considered that the difference between two patterns of distribution was caused by the different methods of selecting the locations for the indoor measurements and of obtaining the outdoor dose (see the Methods section), and by the different geographical conditions of house locations. In the CEX-59.13, the ground around the house was approximately flat.

When the representative range of 0.2 to 0.5 in the IAEA-TECDOC-1162[7] document was considered, only 66.5% of all of the data were covered, indicating that this range was narrow. A total of 80.7%, 87.7%, and 93.3% of the data were covered when the representative ranges of 0.2 to 0.6, 0.2 to 0.7, and 0.2 to 0.8, respectively, were considered. The wider range of 0.2 to 0.7 or at least 0.2 to 0.6 is recommended as the representative range.

It should be noted that in Fig. 3, 10.0% of the data were within the range of 0.7 to 1.4 of the higher reduction factor value. These data within the range of 0.7 to 1.4 was examined in detail as follows: Twenty houses (29.4%) had a room in which the reduction factor exceeded 0.7. Ten of these houses had only one room, while the remainder had multiple rooms with the reduction factor value greater than 0.7. Two factors were considered to influence the reduction factor. One was location of the room in the house and area topography, and the other was the cement roof tiles. For the former, some rooms showed a high reduction factor including those where the reduction factor exceeded 1 (five data sets for three rooms in Iitate village) and were located facing a steep upward slope of a hill or a mountain and their dose rates were greater than those of others in the same building. The rooms were directly affected by surface
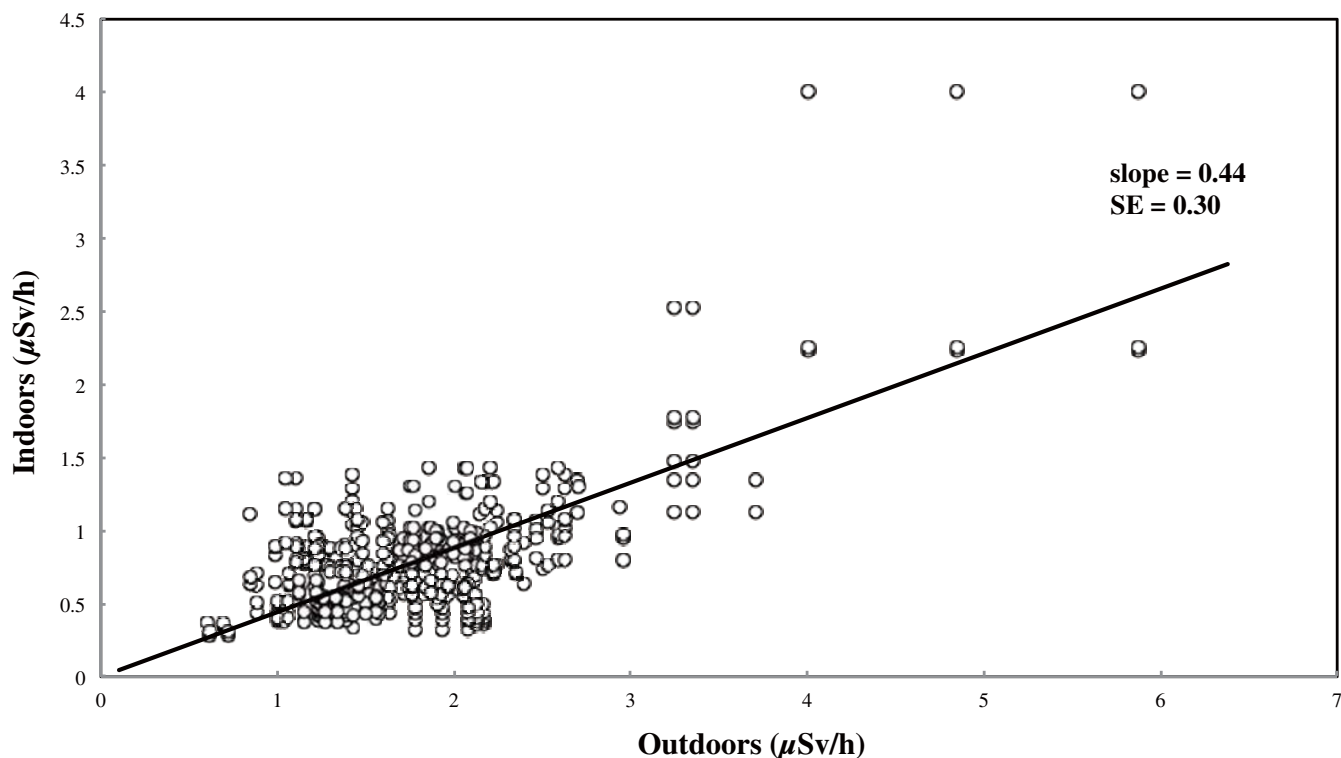
slope = 0.44
SE = 0.30

Figure 2 | Relationship between the indoor and outdoor ambient dose equivalents.

deposition on the slope of the hill or the mountain and the accumulated fallen leaves to which radionuclides were attached. The contaminated top layer of soil that slid down the slope accumulated in the back side of the house, giving an influence on their dose rates as well. Moreover, in this study the outdoor measurements were consistently collected from locations in an open field in an uncovered yard (see the Methods section). The appropriate locations for outdoor measurements were found only in the front of the house, especially in Iitate village, where many houses stand on the lower slope of a hill or a mountain, having a steep upward slope at the back and the side. This resulted in a large reduction factor because the dose rates in the front of the houses were not affected by the back and the side, and were lower compared with those in the backyard. The reduction factor data exceeding 1 were not excluded from the statistical analysis

to obtain the median as the median can reduce the importance attached to a few outliers. It is also noted that the practical reduction factors based on the dose in the front side, which are obtained consistently and easily, are useful in estimating the indoor dose in the evacuation zone with a hill or a mountain.

Based on the result in Table 1, the frequency distribution of the reduction factor for the living room (located on the front side of the house) was compared with that for the rooms on the back facing the backyard (the bedroom and other rooms) (Fig. 4). The median for the living room and for the rooms on the back were 0.38 (0.31–0.47) and 0.49(0.41–0.62), respectively. As shown in Fig. 4, the frequency of the back rooms shown as red bars had a larger reduction factor value. This result indicated a close relationship between the location of the rooms, the use and purpose of the rooms, and the
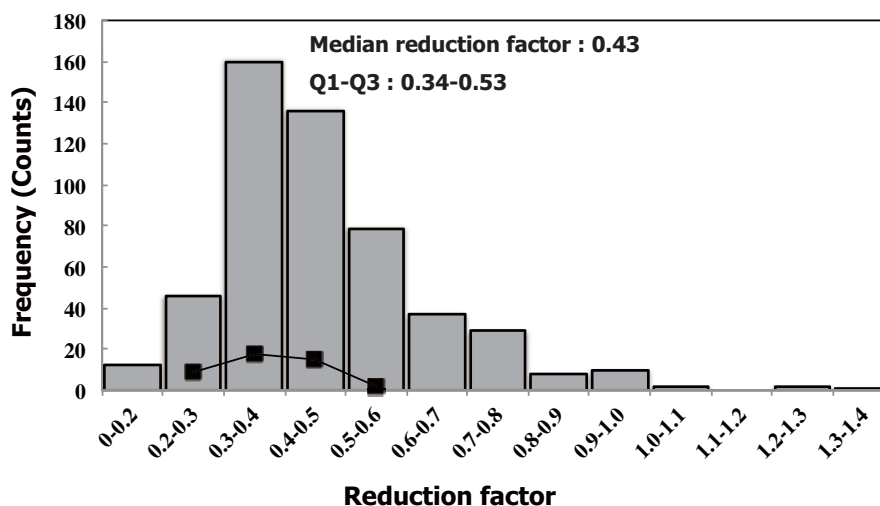

Figure 3 | Frequency distribution of the reduction factor. The median reduction factor with an interquartile range is 0.43 (0.34–0.53). The frequency reduction factor distribution measured experimentally for wooden frame houses, which is referred to as the CEX-59.13[16], is also plotted as closed squares.

Table 1 | The type, the location, number of rooms where the indoor measurements were collected, and the median reduction factor with an interquartile range

First floor	Location*	Numbers	Reduction factor**	Second floor	Numbers	Reduction factor
Living room	F	80	0.38 (0.31–0.47)	Room for all purposes	32	0.46 (0.39–0.55)
Bedroom	B	40	0.49 (0.40–0.61)	Child's room	19	0.44 (0.40–0.56)
kitchen	F,B,F&B	13	0.34 (0.32–0.44)	Bedroom	17	0.44 (0.37–0.52)
Child's room	F,B	6	0.54 (0.46–0.93)	Living room	1	0.58 (0.52–0.60)
Others	F	15	0.39 (0.32–0.43)	Attic	2	0.53 (0.52–0.53)
	B	7	0.51 (0.42–0.67)	Freestanding small house	2	0.60 (0.55–0.61)
Freestanding small house	-	2	0.69 (0.51–1.23)			
All data at first floor	(163)		0.41 (0.33–0.53)	All data at second floor	(73)	0.45 (0.38–0.56)
Total					236	0.43 (0.34–0.53)

*F and B indicate the location of the room within the house. F: on the front of the house, B: on the back of the house, F&B: facing the both sides. Most rooms on the second floor are located on the front side of the house.
**Reduction factors are expressed as the median (Q1–Q3).

pattern of the reduction factor for rooms on the first floor. It also indicates that spending more time in the living room on the front side of the house can reduce residents' exposure dose rather than in the rooms on the back after a nuclear accident. With regard to the rooms on the second floor, no clear relationships were observed because most of the rooms investigated were located on the front side. There was no statistically significant difference between the reduction factor of the rooms on the first floor and that of the rooms on the second floor.

In this study, there were eighty-one roofs as twelve houses had two different types of roofs. Forty-four (54.3%) were tiled roofs, thirty (37.0%) were galvanized-iron roofs, and seven (8.6%) were cement tile roofs. Four of seven cement tile roofs gave large reduction factor values ranging from 0.7 to 1.0 to all the rooms below. In Odaka district, there were two mixed-type houses with a tiled roof and a cement tile roof for different buildings. For both houses, the reduction factor for the rooms with cement roof tiles only exceeded 0.7, but that for the rooms with the tiled roof did not. In measurements using the survey meter collimated with the 5-cm-thick lead, we changed the direction of the uncovered top of the probe to the six directions of east, west, north, south, up and down. The radiation from the upper

direction was high in the rooms with cement roof tiles, although trees did not grow around the house. This tendency was not often observed in the rooms with a tiled roof or galvanized-iron roof, indicating that radiation from the cement roof tile increased the dose rate inside the room, resulting in a larger reduction factor value. In order to examine this hypothesis, dose rate at a height of 1 m above the floor in the room below the cement tile roof was calculated using a Monte Carlo method. The concentrations of ^{134}Cs and ^{137}Cs in cement roof tiles collected from the roof of a house in Hippo in June 2013 were used for the calculation. Hippo is located approximately 53 km northwest of the FDNPP and 10 km distant from Iitate village. This area is not in the evacuation zone, but was strongly affected by large amounts of radionuclides deposited northwest of the FDNPP[5]. Five tiles were collected from the roof and moss growing on the surface was removed. The tiles were crushed into approximately 0.5×0.5 cm pieces and samples were analyzed for radionuclides using a gamma-ray spectroscopy. Gamma-ray emissions at energies of 0.604 and 0.796 MeV (^{134}Cs) and 0.662 MeV (^{137}Cs) were measured for 3,600 s using a high-purity germanium (HPGe) detector (CANBERRA Industries Inc., USA). The highest
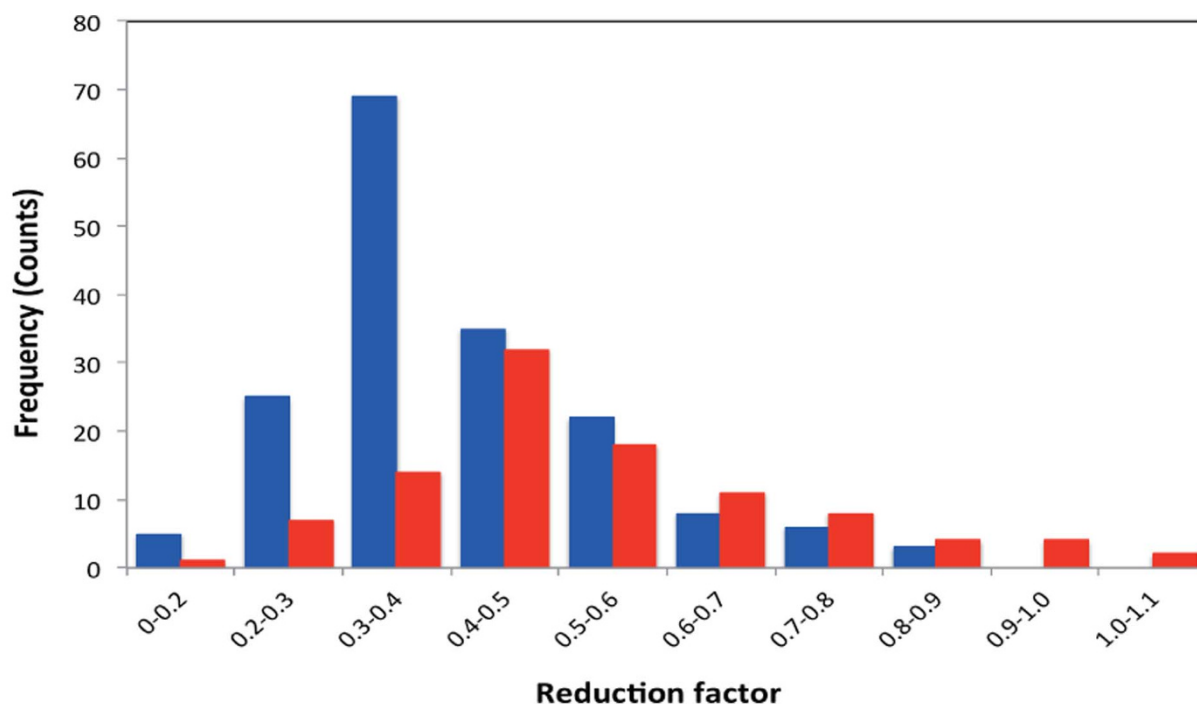

Figure 4 | Comparison of the frequency distribution of the reduction factor for the living room (blue bars) and that for the rooms on the back facing the backyard (red bars).

concentrations of ^{134}Cs and ^{137}Cs corrected to the sampling date were 3,162 ± 23 and 6,756 ± 30 Bq/kg, respectively. Assuming that the roof is a surface source containing the highest concentrations of ^{134}Cs and ^{137}Cs observed, the dose rate for a room of 3.6 m × 3.6 m × 2.5 m H below the roof was calculated. The results were 0.042 and 0.033 μSv/h for ^{134}Cs and ^{137}Cs, respectively. The total dose rate of 0.075 μSv/h was approximately 30% of the indoor dose rate of 0.24 μSv/h, which was measured using the scintillation survey meter TCS-172B on the sampling date. This result may have been over-estimated as the highest concentrations of radionuclides were used for the calculation, however, it is noted that the ^{137}Cs deposition level in the roof tile in Iitate village and Odaka district was much higher than that in Hippo as the absorption of radionuclides into the cement roof tile was caused by wet deposition due to rainwater and may be proportional to the deposition concentration to the ground.

Other than the differences mentioned above, no factors influencing the reduction factor, such as the difference in the values of $H^*(10)_{in}$ or $H^*(10)_{out}$ in the area between Iitate village and Odaka district between Area 1 and Area 2, were observed in this study. We previously reported the contamination of internal surfaces[17]. The possible influence of indoor contamination on the reduction factor has been reported in other papers[7,18,19]. In the IAEA-TECDOC-1162, the reduction factor values are appropriate if indoor deposition is negligible[7]. Our preliminary study in Iitate village indicates that indoor surface contamination observed inside of the house was low, thus, its influence on the reduction factor was negligible in Iitate village. We have investigated indoor surface contamination in Odaka district, and will determine the influence of indoor surface contamination on the reduction factor in a future study.

Methods

Locations of measurements. From December 2012 to December 2013, indoor and outdoor dose measurements were collected in Iitate village and Odaka district in Minami-Soma, Fukushima Prefecture, where both of these administrative districts have been designated as an evacuation zones. Iitate village is located in 29–49 km northwest of the FDNPP, and Odaka district is within a 20 km radius of the FDNPP that used to be designated as a restricted area. The locations of the measurements are shown in Fig. 1 as blue, closed circles. The size of the blue, closed circles depends on the number of houses investigated at each location. In these rural areas, houses are commonly a considerable distance from each other with a large yard in front of the main house. Iitate village forms a basin surrounded by a mountain and is nearly 75% forested. Many houses in Iitate village and some in Odaka district are on the lower slope of a hill or a mountain and cut through the slope. Rooms in the back of these houses are commonly very close to the skirt of a hill or a mountain. Most people live in a multi-family dwelling, allowing three generations of a family to live together. Some houses have been remodeled and/or the main house has been altered. In such a mixed-type house, different types of roof tiles are sometimes used on the new building.

Measurements of indoor and outdoor doses. The ambient dose equivalents were measured indoors and outdoors using the 1″ φ × 1″ NaI (Tl) scintillation survey meter TCS-172B (Hitachi Aloka Medical, Ltd., Japan). The reduction factor, RF, is defined as the ratio of indoor ambient dose equivalents [$H^*(10)$] to that outdoors as follows:

$$RF = H^*(10)_{in}/H^*(10)_{out} \qquad (1)$$

where RF is the reduction factor; $H^*(10)_{in}$ is the indoor ambient dose equivalent at the center of the room away from doors and windows at a height of 1 m above the floor; and $H^*(10)_{out}$ is the outdoor ambient dose equivalent at a height of 1 m above the ground. At each point, measurements were collected by changing the direction of the probe of the survey meter to the four directions of east, west, north, and south, and each measurement was repeated three times. An average of twelve data points was used for the calculations.

Fifty-nine houses (22 in Area 1 and 37 in Area 2) in Iitate village and ten houses (9 in Area 1 and 1 in Area 2) in Odaka district (sixty-nine houses in total) were investigated. The indoor measurements were collected from two to four rooms where the residents spend much of their time, such as a living room, a bedroom, and a child's room. The $H^*(10)_{in}$ ranged from 0.28 to 4.00 μSv/h. The type and number of rooms where the indoor measurements were collected are shown in Table 1. The outdoor measurements were collected from one to four locations in an open field in an uncovered yard. These locations were selected from the front side of the main house because the backyard was small and quite close to the skirt of a hill or a mountain facing the soil surface of the slope in most houses, especially those in Iitate village. The $H^*(10)_{out}$ ranged from 0.60 to 5.88 μSv/h. The reduction factor was obtained using

Eq. (1), including every combination of $H^*(10)_{in}$ and $H^*(10)_{out}$ from each house. The coefficient of variation (CV) for the values of $H^*(10)_{out}$ associated to the same value of $H^*(10)_{in}$ ranged from 0 to 45.3%. The median coefficient of variation with an interquartile range was 9.72% (4.6%–24.2%). The reduction factor data exceeding 1 were not excluded from statistical analysis. The data obtained during the time of snow cover were excluded. All of the measurements were collected before decontamination began. It is noted that the difference in methods of selecting the locations for the indoor measurements and of obtaining the outdoor dose between in this study and in the experimental study utilizing ^{60}Co reported in the CEX-59.13[16]. For the latter, the readings of dosimeters placed along the axis which ran through the center of the house were used as the indoor dose and the infinite-plane dose rate at a height of 1 m was used as the outdoor dose.

In measuring the $H^*(10)_{in}$, further measurements were collected using the survey meter collimated with 5-cm-thick lead. In the calculations, 5-cm-thick lead reduced incident gamma-ray emission from ^{137}Cs and ^{134}Cs (gamma emission energy of 0.662 MeV from the former and 0.605, 0.796, and 0.802 MeV from the latter), dominant nuclides in the affected area, to less than 1/100. The shielding of 5-cm-thick lead was confirmed by irradiating the survey meter with a point source of ^{137}Cs. There was no effect on the reading of the survey meter until $H^*(10)$ exceeded 1.0 μSv/h, and then the reading began to increase slightly. By covering the probe of the survey meter except the top with lead, we detected only incident gamma-ray emissions in the uncovered direction, while minimizing the effect of incident radiation from other angles.

The gamma ray energy spectra were measured indoors and outdoors in the same way using the 3″ φ × 3″ NaI (Tl) scintillation spectrometer JSM-112B (Hitachi Aloka Medical, Ltd., Japan). The counting time was set to 900 s at every measurement. The obtained gamma-ray pulse height distributions were unfolded with the 22 × 22 response matrix method for the evaluation of concentrations of potassium, uranium, and thorium[20]. The absorbed dose rate in the air, obtained as nGy/h, due to natural radiation sources in the environment was estimated using the conversion factors (13.0 nGy/h per % for potassium, 5.4 nGy/h per ppm for uranium, and 2.7 nGy/h per ppm for thorium) as evaluated by Beck et al.[21].

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Acknowledgments

Author contributions

H.Y. designed the study. H.Y., T.K., M.U. and H.T. conducted in situ measurements in evacuation zones. M.H. analyzed the gamma ray energy spectra. H.Y. wrote the text and made tables and figures. H.Y. and M.H. contributed extensively to discussions about this work. All authors reviewed the manuscript.

Additional information

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