HIROSAKI UNIVERSITY

REM
Radiat Environ Med

Radiation Environment and Medicine 2018 Vol.7, No.1 21–27

Regular Article

Measurement of Gamma Radiation at Junior High School Sites in Fukushima City

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Received 13 June 2017; revised 25 September 2017; accepted 28 September 2017

The present study aimed at providing gamma radiation levels from natural radionuclides for Fukushima City (Fukushima Prefecture, Japan) and clarifying the contribution of the artificial radionuclides derived from the 2011 Fukushima Dai-ichi Nuclear Power Plant accident to external radiation exposure. Air-kerma rates from them were measured with a 3 in × 3 in NaI(Tl) scintillation spectrometer outdoors and indoors at junior high school sites in the summer of 2014 after decontamination activities had been completed. The results showed that the outdoor and indoor air-kerma rates from the natural radionuclides were about 0.04 μGy h^{-1} and 0.03 μGy h^{-1}, respectively. Those from the artificial radionuclides were about 0.03 μGy h^{-1} for outdoors and 0.01 μGy h^{-1} for indoors. At almost all sites, the natural gamma radiation dominated external gamma radiation exposure on the measurement dates.

Key words: Cesium, Dose rate, External exposure, Natural radiation, Nuclear accident, Radionuclide

1. Introduction

The 2011 Fukushima Dai-ichi Nuclear Power Plant (FDNPP) accident caused radioactive contamination in Fukushima Prefecture, Japan. Since then, the residents have been exposed to radiation from accident-derived artificial radionuclides (e.g. ^{134}Cs and ^{137}Cs) in addition to natural gamma radiation (hereafter, natural radiation) emitted from ^{238}U- and ^{232}Th-series elements and ^{40}K in soil and building materials. The exposure to the artificial radionuclides (i.e. additional dose) will become less important, while that to the natural radionuclides will become more important with decreasing gamma radiation level from the artificial radionuclides due to decontamination activities, radioactive decay and weathering effects. Thus, for the residents to know the exposure to the additional dose, not only absolute levels of gamma radiation, but also those from the artificial radionuclides and, in particular, the natural radionuclides should be provided.

Fukushima City, which was heavily contaminated, is the third most populous cities (about 280,000 residents[1]) in the prefecture. Only a few measurements have been made to evaluate natural radiation level in this city. The National Institute of Radiological Sciences[2, 3] conducted measurements as a part of nationwide surveys done in the 1960s to 1970s, and the Fukushima Prefectural Atomic Energy Center[4] did in 1995 and 1996. After the FDNPP accident, Omori *et al.*[5] evaluated gamma radiation separately from natural and artificial radionuclides on Fukushima Medical University campus using a spectrometer. In all of these surveys before and after the FDNPP accident, however, the measurements

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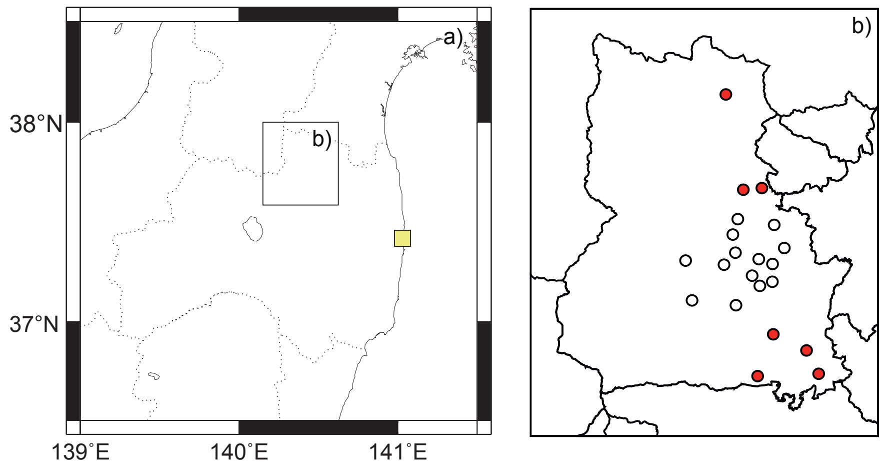

Fig. 1. Location of investigated municipal junior high schools in Fukushima City. The square in panel a) represents the Fukushima Dai-ichi Nuclear Power Plant. The open and solid circles in panel b) represent the municipal junior high schools located in and around the Fukushima basin, respectively. This figure was created using the Generic Mapping Tools[25].

were made at only 1-3 locations in Fukushima City, and such numbers of locations were small for evaluation of the natural radiation level.

In the present study, the gamma dose rates (air-kerma rates) from the natural and artificial radionuclides were evaluated for locations outdoors and indoors in Fukushima City in the summer of 2014. Junior high school sites were chosen as measurement sites because they are located in densely populated areas and their grounds are open with wide, bare dirt surfaces. The present study aimed at providing more natural radiation data for the city and clarifying the contribution of artificial radionuclides to external radiation exposure.

2. Materials and Methods

2.1. Measurement sites

Figure 1 shows locations of municipal junior high schools in Fukushima City. Twenty-one municipal junior high schools existed at the time of the FDNPP accident. However, one was closed in 2014 and abolished one year later and, therefore, 20 schools existed as of 2017. Geographically, 14 schools were located at the bottom of the Fukushima basin, and the other 7 schools were at hilly to mountainous areas surrounding the basin. All of the schools had multi-story (two- to four-story) concrete buildings except for the abolished school which was a two-story wooden building. At the junior high school sites, the Fukushima City government had arranged for workers to carry out decontamination activities to reduce the gamma dose rate elevated by the FDNPP accident. These activities mainly included high-pressure washing of paved surfaces and walls and roofs of school buildings and removing of a topsoil layer (to about 5 cm depth) of schoolyards. The removed topsoil was replaced with the subsurface soil that was below the topsoil on the site. The decontamination was started in May and it was completed for all of the schools in the summer of 2011.

The gamma dose rates and gamma-ray pulse-height distributions were measured outdoors and indoors in July and August, 2014. The outdoor measurements were made at all 21 junior high school sites (arbitrarily assigned letters A to U). In contrast, the indoor measurements were made at 20 sites; the abolished school was excluded (site U). At each school site, measurement points were set: at the center of the schoolyard as an outdoor environment; and at the center of a room on the ground floor level as an indoor environment. In the present study, indoor measurements were not made in other rooms in the ground floor or upper floors. According to previous studies[6, 7], no obvious trend of natural radiation level was observed with respect to the room size of concrete buildings and the number of their stories.

2.2. Measurement of gamma dose rate and pulse-height distribution

The pulse-height distributions of the incident gamma rays were measured and analyzed to separate the radiation according to the source being natural or artificial radionuclides. A 3 in × 3 in cylindrical NaI(Tl) scintillation spectrometer EMF-211 (EMF Japan Co. Ltd., Japan) was used. These measurements were made for 900 s at 1 m above the ground and the room floor at the center point. The pulse-height distributions were unfolded in energies of 0.05-3.2 MeV based on a 22 × 22 response matrix method[8-10] to obtain incident gamma-ray flux density energy spectra. The response matrix method assumes that a radiation field is isotropic and radioactive source distributions are from a semi-infinite homogeneous volume source in the ground for the natural radionuclides

Table 1. Gamma radiation levels from natural and artificial radionuclides, and their ratios

Site	Gamma radiation level								Ratio[a] (artificial/natural)	
	Natural radionuclides				Artificial radionuclides (^{134}Cs + ^{137}Cs)					
	Outdoor		Indoor		Outdoor		Indoor		Outdoor	Indoor
	μGy h^{-1}	μSv h^{-1}	μGy h^{-1}	μSv h^{-1}	μGy h^{-1}	μSv h^{-1}	μGy h^{-1}	μSv h^{-1}	-	-
A	0.030	0.05	0.029	0.04	0.035	0.06	0.007	0.01	1.16	0.23
B	0.037	0.05	0.028	0.04	0.166	0.21	0.009	0.01	4.55	0.31
C	0.044	0.07	0.036	0.05	0.035	0.06	0.008	0.01	0.80	0.22
D	0.029	0.05	0.052	0.07	0.030	0.05	0.007	0.01	1.03	0.13
E	0.030	0.05	0.032	0.04	0.027	0.04	0.007	0.01	0.91	0.23
F	0.043	0.07	0.041	0.06	0.037	0.06	0.010	0.01	0.87	0.24
G	0.039	0.06	0.026	0.04	0.011	0.02	0.007	0.01	0.28	0.28
H	0.034	0.06	0.031	0.04	0.042	0.07	0.005	0.01	1.22	0.17
I	0.046	0.07	0.041	0.06	0.033	0.05	0.009	0.01	0.71	0.23
J	0.030	0.05	0.026	0.04	0.013	0.02	0.005	0.01	0.44	0.18
K	0.034	0.06	0.042	0.06	0.006	0.01	0.004	0.01	0.16	0.10
L	0.031	0.05	0.027	0.04	0.024	0.04	0.005	0.01	0.77	0.20
M	0.036	0.06	0.048	0.07	0.024	0.04	0.006	0.01	0.67	0.12
N	0.044	0.07	0.042	0.06	0.038	0.06	0.007	0.01	0.88	0.17
O	0.038	0.06	0.026	0.04	0.027	0.04	0.004	0.01	0.71	0.15
P	0.043	0.07	0.046	0.06	0.009	0.02	0.006	0.01	0.22	0.13
Q	0.033	0.05	0.028	0.04	0.013	0.02	0.005	0.01	0.39	0.17
R	0.030	0.05	0.030	0.04	0.018	0.03	0.006	0.01	0.58	0.20
S	0.041	0.07	0.031	0.04	0.013	0.02	0.004	0.01	0.32	0.12
T	0.026	0.04	0.028	0.04	0.030	0.05	0.007	0.01	1.13	0.26
U	0.048	0.08	-	-	0.012	0.02	-	-	0.24	-
Average	0.037	0.06	0.034	0.05	0.031	0.05	0.006	0.01	0.86	0.19
Standard deviation	0.006	0.01	0.008	0.01	0.033	0.04	0.002	0.00	0.91	0.06
Minimum	0.026	0.04	0.026	0.04	0.006	0.01	0.004	0.01	0.16	0.10
Median	0.036	0.06	0.031	0.04	0.027	0.04	0.006	0.01	0.71	0.19
Maximum	0.048	0.08	0.052	0.07	0.166	0.21	0.010	0.01	4.55	0.31

[a] Ratio of air-kerma rate from artificial radionuclides to that from natural radionuclides.

and an infinite plane source for ground-deposited artificial radionuclides.

The air-kerma rates from natural radiation were evaluated based on the flux density at the photon peaks of ^{40}K (1.464 MeV), ^{214}Bi (1.765 MeV and 2.205 MeV), and ^{208}Tl (2.615 MeV). Those for artificial radionuclides (^{134}Cs and ^{137}Cs) were determined from the residual flux density in the 0.05-0.85 MeV energy bins after the contributions from natural radiation were excluded. The residual flux density was also divided into primary and scattered components. The scattered components overlapping on the primary components in the 0.45-0.85 MeV energy bins were evaluated by a linear interpolation method.

2.3. Conversion of air-kerma rate to ambient dose rate

For the general public, the evaluated air-kerma rate (μGy h^{-1}) may not be a well-known quantity; they are more familiar with ambient dose rate (ambient dose equivalent rate; μSv h^{-1}). Thus, the ambient dose rate was shown together with the air-kerma rate. Conversion equations were obtained by comparison between the air-kerma rate and ambient dose rate. The ambient dose rate was measured using a 1 in × 1 in cylindrical NaI(Tl) scintillation survey meter TCS-172B (Hitachi-Aloka Medical Ltd., Japan) that was calibrated by gamma rays from a ^{137}Cs source. In addition, the survey meter had a nearly constant energy response within ± 15% relative to ^{137}Cs by applying a spectrum-dose conversion operator $G(E)$ function for unidirectional irradiation to a gamma-ray pulse-height distribution without unfolding the energy spectrum[11]. According to Tsuda and Saito[11], the TCS-172B survey meter possibly measures ambient dose rate conservatively by up to +20-30% for gamma rays with energies around a few hundred kilo electron volts in environmental radiation measurements due to different irradiation geometries between the environment and the condition of the operator $G(E)$ function. However, it is regarded as a standard detector, and it has been frequently used in, for instance, dose mapping projects[12] after the FDNPP accident. The measurement points were the same as those for the air-kerma rate, and the measurements were made five times at 1 m above the ground and the room floor at each point.

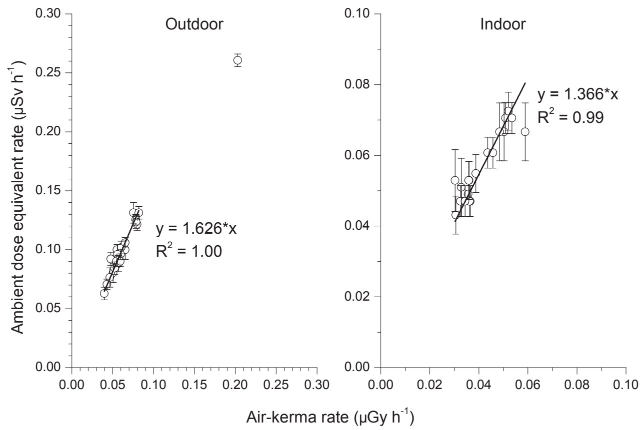

Fig. 2. Scatter plots of ambient dose equivalent rate against air-kerma rate outdoors and indoors.

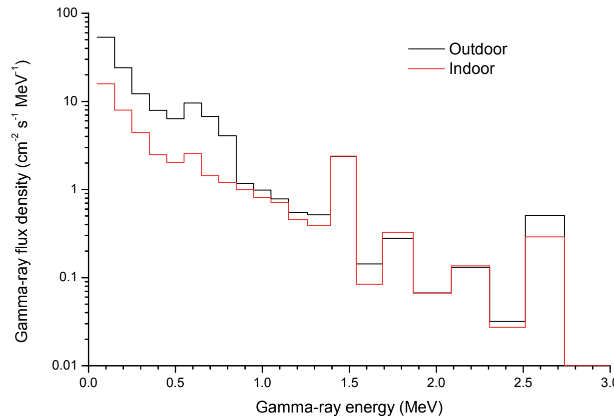

Fig. 3. Incident gamma-ray flux density measured at school site H.

3. Results and Discussion

3.1. Comparison between air-kerma rate and ambient dose rate

Gamma radiation levels outdoors were 0.040-0.203 μGy h^{-1} as air-kerma rate and 0.06-0.26 μSv h^{-1} as ambient dose rate. The corresponding values for indoors were 0.030-0.059 μGy h^{-1} and 0.04-0.07 μSv h^{-1}. According to measurement results presented by Fukushima City government[13], the ambient dose rates were 0.22-3.63 μSv h^{-1} for outdoors and 0.16-0.73 μSv h^{-1} for indoors two to three months after the FDNPP accident. The ambient dose rates had decreased by one to two orders of magnitude until the present measurement dates due to the decontamination activities, radioactive decay and weathering effects. Details of the gamma radiation levels at each site are shown in Table 1.

The ambient dose rates were higher than the air-kerma rates for all measurement locations. To determine the relationship between the air-kerma rate and ambient dose rate, scatter plots of the ambient dose rates outdoors and indoors against the air-kerma rates are shown in Figure 2. Positive correlations were found between them, both outdoors and indoors. Regression lines through the origin could be also determined with high values (0.99-1.00) of corrected determination coefficients. The highest dose rate datum for outdoors was excluded for the regression analysis (the reason is given below). The slope of the regression line for outdoors was evaluated as 1.63 Sv Gy^{-1} (standard error: 0.02 Sv Gy^{-1}), which was higher than the slope 1.37 Sv Gy^{-1} (standard error: 0.03 Sv Gy^{-1}) for indoors. In addition, these values were 1.1-1.3 times higher than the ratio (around 1.25 Sv Gy^{-1}) of ambient dose rate to air-kerma rate obtained by a simulation[14] and observations in Fukushima Prefecture in the dose mapping projects[12, 15].

The different slopes for regression lines, outdoors and indoors, can be attributed to the presence of fallout radionuclides outdoors. As shown in Figure 3, low-energy gamma rays tended to occupy a larger part of the incident gamma-ray flux density outdoors than indoors due to presence of scattered radiation from ^{134}Cs and ^{137}Cs. According to the ICRP Publication 74[14], the ratio of ambient dose rate to air-kerma rate increases with decreasing energy of gamma radiation. In addition, the response of the survey meter measuring ambient dose rate increases with decreasing energy of gamma radiation as mentioned in the previous section. These may result in the different line slopes.

The difference in the ambient dose rate to air-kerma rate ratio between the present study and the literature[15] can be attributed to measurement methods. In the dose mapping projects[12, 15], the air-kerma rates and the ambient dose rates were adjusted with the $G(E)$ function. In the present study, the ambient dose rates were measured by the same method, but the air-kerma rates were evaluated based on the response matrix method. As mentioned previously, the ambient dose rate is possibly overestimated for measurements in the environment. In addition, the air-kerma rate based on the response matrix method is systematically lower compared to the $G(E)$ function[16] for a cylindrical NaI(Tl) scintillator.

For the outdoor data sets, the highest dose rate datum was excluded for the regression analysis. This datum was 0.203 μGy h^{-1} as the air-kerma rate and 0.26 μSv h^{-1} as the ambient dose rate at site B. The ratio was 1.28 Sv Gy^{-1}, which was lower than 1.63 Sv Gy^{-1} obtained from the other outdoor data sets. This difference may be caused by the amount of ^{134}Cs and ^{137}Cs and dominant components of primary and scattered radiation. According to the observations in Bryansk, Russia[17], lower values of the ratio were observed at sites where the primary radiation dominated the air-kerma rate after the Chernobyl accident. As shown in the next subsections and Table 1, significantly large amount of ^{134}Cs and ^{137}Cs contributed to

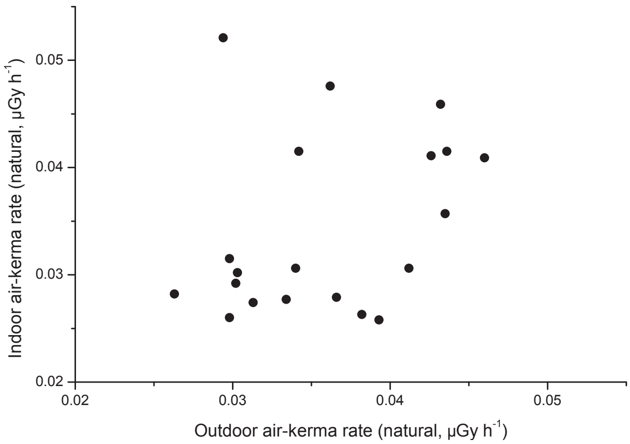

Fig. 4. Scatter plots of indoor air-kerma rate against outdoor air-kerma rate from natural radionuclides.

air-kerma rate and ambient dose rate at site B. In addition, primary gamma-ray flux relative to scattered gamma-ray flux was about 0.45, which was the second highest value among all measurement sites (the highest value was 0.54 at site U, but gamma radiation from the natural radionuclides dominated air-kerma rate and ambient dose rate). Consequently, the lowest value of the ratio was obtained at site B and, therefore, the datum was excluded for the regression analysis.

Based on the above, the following equations were applied for conversion from air-kerma rate D to ambient dose rate H:

$H = 1.626 \times D$ for the outdoor sites, except site B,
$H = 1.284 \times D$ for the outdoor site B,
$H = 1.366 \times D$ for the indoor sites.

The ambient dose rates from natural radionuclides and those from artificial radionuclides were calculated according to the absolute value of the ambient dose rate and the constituent ratio of natural and artificial radionuclides in the air-kerma rate.

3.2. Radiation level from natural radionuclides

Table 1 summarizes outdoor and indoor air-kerma rates contributed from natural radionuclides. Average outdoor air-kerma rate was 0.037 ± 0.006 μGy h^{-1} (range: 0.026-0.048 μGy h^{-1}), while average indoor air-kerma rate was 0.034 ± 0.008 μGy h^{-1} (range: 0.026-0.052 μGy h^{-1}). At most (14/20) of the school sites, the indoor air-kerma rate was slightly lower than the outdoor air-kerma rate, by a factor of 0.97 ± 0.25 on average (median: 0.93; range: 0.66-1.77). Figure 4 shows a scatter plot of the indoor air-kerma rate against the outdoor air-kerma rate. No correlation was found between them. It should be noted, again, that the indoor air-kerma rates were measured only in the schools with concrete buildings.

Nationwide-surveys conducted by the National Institute of Radiological Sciences[2, 3] revealed that outdoor air-kerma rates were 0.04-0.08 μGy h^{-1} in Fukushima Prefecture and 0.05 μGy h^{-1} in Fukushima City, while the Fukushima Prefectural Atomic Energy Center[4, 18] reported that the corresponding values were 0.02-0.07 μGy h^{-1} and 0.04 μGy h^{-1}. After the FDNPP accident, outdoor measurements gave a value of 0.03 μGy h^{-1} on the Fukushima City campus of Fukushima Medical University[5]. In addition, natural radiation of 0.04 μGy h^{-1} has been assumed to estimate additional external doses following the FDNPP accident[19, 20]. In the present study, the outdoor air-kerma rates were 0.03-0.05 μGy h^{-1}, which was in good agreement with the previous studies.

No nationwide Japanese survey has been made for air-kerma rates in concrete buildings, but a few surveys were made in specific areas. Matsuda *et al.*[6] measured air-kerma rates in concrete model houses (n = 7) in Nagoya City and determined their average was 0.08 ± 0.01 μGy h^{-1} (range: 0.07-0.10 μGy h^{-1}). Saito *et al.*[7] reported 0.05 ± 0.01 μGy h^{-1} (range: 0.02-0.08 μGy h^{-1}) in concrete houses (n = 103) and 0.05 ± 0.01 μGy h^{-1} in concrete office buildings (n = 58) in metropolitan Tokyo and its surrounding prefectures. After the FDNPP accident, Omori *et al.*[5] obtained 0.03 μGy h^{-1} in a concrete building housing laboratories (Fukushima City). The present indoor air-kerma rates from the natural radionuclides agreed better with the results of Omori *et al.*[5] and Saito *et al.*[7] than with those of Matsuda *et al.*[6]

The present indoor air-kerma rate was slightly lower than the outdoor air-kerma rate. This tendency was comparable to the result (0.95 ± 0.15) of Matsuda *et al.*[6] In addition, no correlation was found between the indoor and outdoor rates as shown in Figure 4. This may mean that the indoor air-kerma rate is caused mainly by the presence of the natural radionuclides in building materials.

3.3. Radiation level from artificial radionuclides

Gamma-ray pulse-height distribution obtained by the spectrometer measurements confirmed the presence of gamma radiation from the artificial radionuclides ^{134}Cs and ^{137}Cs. Their amounts were larger outdoors than indoors. Table 1 also summarizes outdoor and indoor air-kerma rates contributed from artificial radionuclides. Average outdoor air-kerma rate was 0.031 ± 0.033 μGy h^{-1} (range: 0.006-0.166 μGy h^{-1}). Excluding site B, the outdoor air-kerma rates were 0.006-0.042 μGy h^{-1}. In contrast, average indoor air-kerma rate was 0.006 ± 0.002 μGy h^{-1} (range: 0.004-0.010 μGy h^{-1}). The indoor air-kerma rates were 5-75% of the outdoor air-kerma rates.

Presence of gamma radiation from the artificial radionuclides indoors can be discussed from two viewpoints. One is penetration of gamma radiation from the artificial radionuclides deposited outdoors. Gamma radiation can pass through windows and building walls, even those made from bricks and concrete. Indoor dose rate relative to outdoor dose rate has been reported to be about 0.05 for a ground-floor room in multi-story buildings[21-23]. The other is presence of radioactive contamination in the investigated rooms. The artificial radionuclides can enter rooms on aerosols suspending in the air[24] and can be carried inside on the bodies and clothing of people. The present study did not clarify which artificial radionuclides deposited outside or inside contributed to the indoor air-kerma rates.

The air-kerma rates from the artificial radionuclides were compared to those from the natural radionuclides. Their ratios (artificial/natural) are shown in Table 1. The ratios for outdoors were 0.16-4.55. Except for site B, the outdoor air-kerma rates from the artificial radionuclides were approximately equal to or lower than those from the natural radionuclides. In contrast, the ratios for indoors were 0.10-0.31, and the indoor air-kerma rates from the artificial radionuclides were significantly lower than those from the natural radionuclides. Thus, at almost all sites, the contribution of natural radionuclides dominated external gamma radiation exposure in the summer of 2014.

4. Conclusion

The measurements of outdoor and indoor gamma radiation levels, separating the contributions of natural and artificial radionuclides, were conducted at junior high school sites in Fukushima City, Fukushima Prefecture in the summer of 2014 after decontamination activities had been completed. The levels of the natural gamma radiation outdoors and indoors were comparable to those observed in Fukushima Prefecture and the other prefectures in Japan. The outdoor levels of gamma radiation from the artificial radionuclides were equal to or less than those of the natural radiation at all sites except one, while the indoor levels were 10-30% of those of the natural radiation at all sites. On the measurement dates, the natural gamma radiation dominated external gamma radiation exposure. These findings are valuable not only for local governments to examine effectiveness of the decontamination activities and establish radiation protection strategies, but also for conducting risk communication with residents, in particular school students and their families.

The present survey provides natural radiation data for Fukushima City. Further surveys are required to clarify effects of the nuclear accident throughout Fukushima Prefecture. In particular, indoor natural radiation levels should be determined for various types of houses and buildings; such data are lacking and obtaining them would contribute to accurate evaluation of additional radiation exposure associated with the FDNPP accident.

Acknowledgement

The present survey was conducted in cooperation with Government of Fukushima City and the municipal junior high schools. The authors would like to thank Mr. S. Endo for arranging the survey.

Conflict of interest disclosure

The authors declare that they have no conflicts of interest.

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