Initial substantial reduction in air dose rates of Cs origin and personal doses for residents owing to the Fukushima nuclear accident

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The initial substantial reduction in the air dose rate and personal dose equivalent [Hp(10)] for residents were compared between the Marumori and Kosugo regions for the period from September 2011 to September 2012 after the occurrence of the Fukushima nuclear accident. Marumori is a rural settlement, and Kosugo is a suburban city along a freeway. A similar tendency was observed in the Hp(10) results for Marumori residents and in the air dose rates for both regions: values dropped during the heavy snow season and a faster reduction in the air dose rate than the radioactive decay of ^{134}Cs and ^{137}Cs was observed after the snow had thawed. These reductions are considered to be caused by the weathering and/or migration of radionuclides down the soil column. However, neither a drop due to an accumulation of snow nor faster reduction was observed in Hp(10) for Kosugo residents. This discrepancy between the air dose rate and Hp(10) for Marumori and Kosugo residents might be caused by differences in their living environment.

Key Words: *initial reduction, personal dose, residents, weathering, air dose rate, Fukushima accident*

1. Introduction

The magnitude 9.0 earthquake and tsunami that occurred on 11 March 2011 in Japan resulted in severe damage to the Fukushima Daiichi nuclear power plant (NPP), and this caused a month-long release of radioactive materials into the atmosphere. Aerial measurements reported by the Ministry of Education, Culture, Sports, Science and Technology, Japan (MEXT) survey showed that the radioactive plumes spread in the northwest direction from the NPP, causing significant radionuclide deposition in that area. Marumori and Kosugo, which are located in Miyagi, a neighboring prefecture to Fukushima, are located 46 km northwest of the NPP at the closest approach (Fig.1). A distribution map of the radioactivity concentration in the soil[1)] published by MEXT showed the presence of several radioactive plumes in this area and the ^{137}Cs deposition level ranged from 100 to 300 kBq/m^2. After the decay of ^{131}I (with a half-life of 8 d), radiation doses since June can be primarily attributed to Cs nuclei. When an initial substantial reduction in the air dose rate is observed, which is expected to occur as a result of the weathering, physical decay, and migration of radionuclides down the soil column[2–4)], the dose for residents is expected to reduce in the same pattern.

In this study, the values of air dose rates in Marumori and Kosugo regions were analyzed to investigate their temporal variation due to Cs nuclei, and the personal dose equivalent [Hp(10)] for residents in those regions was

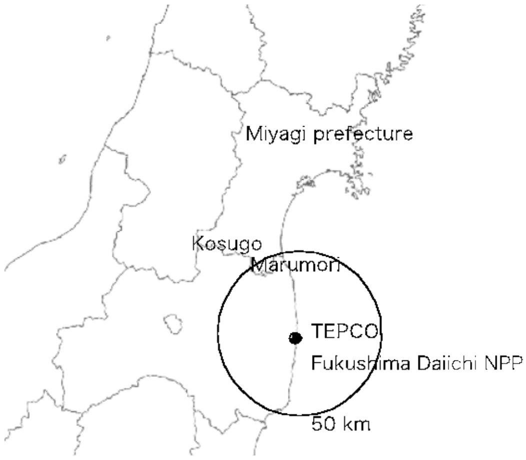


Fig. 1 Locations of Marumori and Kosugo.

evaluated using optically stimulated luminescent (OSL) dosemeters. Then, the initial substantial reduction in the air dose rate and personal dose for residents were compared and the discrepancy between them was discussed.

2. Methods

The *H*p(10) for 54 Marumori and 71 Kosugo residents (125 in total) was evaluated starting 1 September 2011 and 16 December 2011, respectively, until the beginning of September 2012. The territories in Marumori for which data were collected were geographically divided into three regions, Kawadaira, Hippo, and Koya, because the ^{137}Cs deposition levels varied markedly in these regions[1]. The residents whose *H*p(10) were measured consisted mainly of preliminary-school children, pre-school children, and the adults in their families, including indoor workers (teachers and office workers) and outdoor workers (forestry). The measurements were carried out using OSL personal dosemeters and an OSL reader (InLight badge and microStar system, Nagase Landauer, Ltd.). In this study, readings were repeated three times. According to the specifications of the system, doses in excess of 100 μSv are measured within ±10 % standard deviation for an average value of three readings. Dosemeters were calibrated following the Japanese International Standard JIS Z 4511[5]. The deviation in the energy-independent response for photons from 24 keV to 1.25 MeV is within ±10%. The dosemeters that we used are small devices that can be worn on a neck strap. When worn close to the torso, they measure the radiation exposure of the entire body. Each dosemeter was replaced every 1.5–2 months to obtain readings. The correct way to wear the OSL dosemeter was explained to the residents, and dosemeters were distributed to those who were willing to wear the dosemeters themselves or were willing to strap them onto their children. The residents were instructed to record their daily activities and to confirm that they followed the instructions for wearing the dosemeter correctly for the entire period of time that dosemeters were worn. The dosemeter data collected from individuals who did not follow the instructions were excluded from the analysis. All the procedures performed in this study are in accordance with the ethical guidelines for scientific studies, as stipulated by Tohoku university, and the personal information of the subjects has been carefully protected.

The data for air dose rates in the Marumori and Kosugo regions were acquired from the data that were recorded by the local governments[6,7] through the use of an NaI scintillation survey meter over the period from September 2011 to September 2012, and the temporal variations in the rates due to Cs nuclei after the decay of ^{131}I were investigated.

The measurement data were reflective of the radiation from both the Fukushima Daiichi fallout and natural sources. Therefore, air dose rates and external exposure doses from natural radiations, which were estimated to be 0.51 and 0.63 mSv/y [8], respectively, in Japan (from cosmic radiation and natural terrestrial radiation), were subtracted from each measured value.

3. Results and discussion

The air dose rate data were analyzed by comparing them with the calculated rates that accounted for the radioactive decay of ^{134}Cs and ^{137}Cs. The ^{134}Cs/^{137}Cs activity ratio for Fukushima is close to 1 in most published data[9]. The effective doses E(t) were calculated using Equation (1):

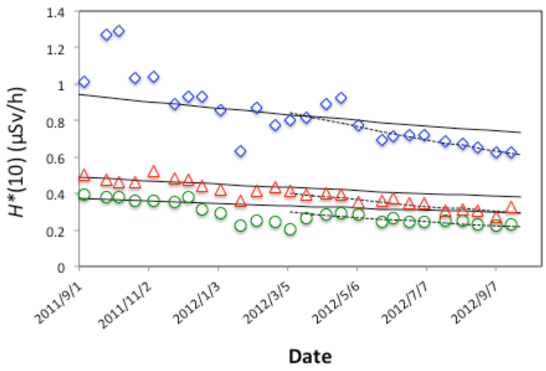
$$E(t) = E(0)/3.7 \times \{ 2.7 \times \exp(-\lambda_1 t) + \exp(-\lambda_2 t) \}, \quad (1)$$

where λ_1 and λ_2 are the decay constants of ^{134}Cs and ^{137}Cs, respectively. From the effective dose rate constants of radionuclides, which are listed in the Table of Isotopes, 10th edition[10], as 0.211 and 0.0779 for ^{134}Cs and ^{137}Cs, respectively, the proportion of ^{134}Cs that contributed to the total effective dose was calculated to be 2.7 times higher than that of ^{137}Cs. The value of E(0) was the measured value for each region, which represented the location factor[2]. In settlements in urban and rural areas, the characteristics of the radiation field differ considerably from those over an open plot of undisturbed land, which is used as the reference site and starting point for calculation of external dose to people from deposited activity. These differences are attributable to varying source distributions as a result of deposition, runoff, weathering and shielding. All such effects can be summarized by the term ‘location factors’[2].

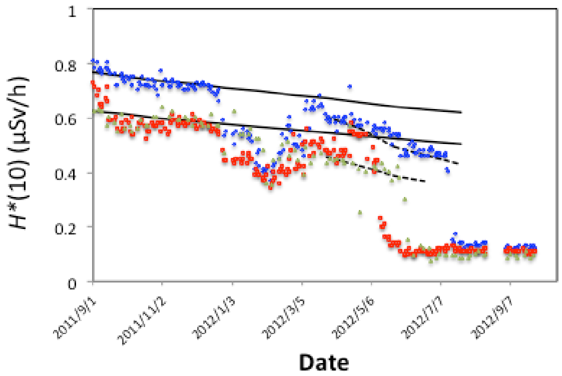
In Figs. 2 (a) and (b), air dose rates in the Marumori and Kosugo regions are shown. In Fig. 2 (a), the values at the three measurement location of Kawadaira (◇), Koya (△), and Hippo (○) are shown. The three measurement locations shown in Fig. 2 (b) are the Kosugo elementary school (◇), a nursery school (□), and a community center (△). The symbols are used indicate measured air dose rate values, and the calculated values obtained by Equation (1) are indicated by solid lines in the figures. The data plotted in Figs. 2 (a) and (b) show similar patterns. The observed long-term decrease in the plotted values is in accordance with the predicted radioactive decay process of ^{134}Cs and ^{137}Cs from summer 2011 to December. During the heavy snow season, air dose rates dropped and remained low from January to early March in 2012. After the snow thawed, the air dose rates returned to previous levels and then followed a relatively faster reduction than the radioactive decay rate of ^{134}Cs and ^{137}Cs. This reduction is considered to be caused by the weathering and/or migration of radionuclides down the soil column[2–4] and might have been accelerated by the melting of snow. The half-lives of this faster reduction in the air dose rate were estimated to be the same at all three measurement locations of the Marumori and Kosugo regions, and only slight differences in half-lives were observed between the two regions. They were estimated as 450 and 300 days in Marumori and Kosugo, respectively, using Equation (2):

$$E'(t) = E'(0) \times \exp(-\lambda_3 t), \qquad (2)$$

where λ_3 is the decay constant. Values calculated using Equation (2) are shown using dotted lines in the figures. In Fig. 2 (b), all the air dose rate values dropped sharply between May and July 2012 because of the decontamination carried out for the yards of elementary school, nursery school, and community center in Kosugo. In Marumori, decontamination had not been carried out at the three measurement locations when measurements were being taken.



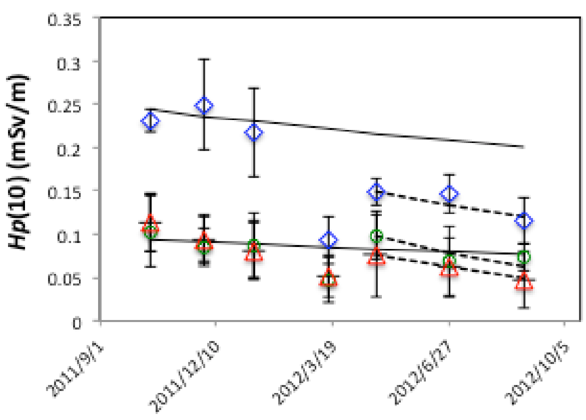
(a)



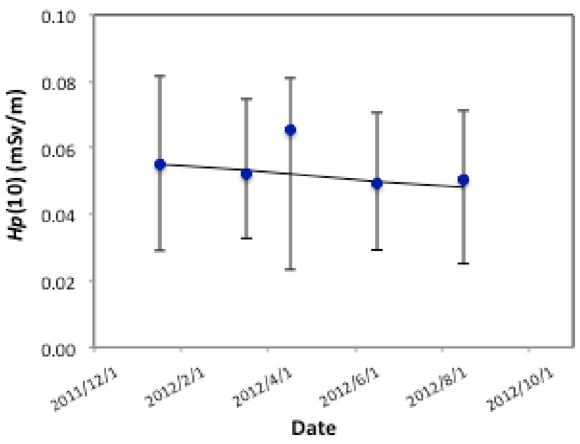
(b)

Fig. 2 Air dose rates in Marumori (a) and Kosugo (b) regions. The values in three measurement locations of Kawadaira (◇), Koya (△), and Hippo (○) are presented (a). Three measurement locations in (b) are the Kosugo elementary school (◇), nursery school (□), and community center (△). Measured values are indicated by marks, and calculated values, which are obtained by Eqs. (1) and (2), are indicated by solid and dotted lines, respectively. A faster reduction than the radioactive decay of ^{134}Cs and ^{137}Cs appears after the thawing of snow.

In Figs. 3 (a) and (b), the *H*p(10) of residents in Marumori and Kosugo regions are shown. The recorded *H*p(10) values for 1.5–2 months were converted into monthly dose. In Fig. 3 (a), average values of *H*p(10) for Kawadaira (◇), Koya (△), and Hippo (○) residents are shown. The average values for Kosugo residents are indicated using circles in Fig. 3 (b). Error bars show 1 standard deviation for each value. The decrease in *H*p(10) for the residents of the Marumori and Kosugo regions differs significantly. The *H*p(10) of Marumori residents show a similar pattern with that observed in air dose rates: values drop during the heavy snow season and faster reduction than the radioactive decay of ^{134}Cs and



(a)



(b)

Fig. 3 *H*p(10) of residents in Marumori (a) and Kosugo (b) regions. Each average value of *H*p(10) for Kawadaira (◇), Koya (△), and Hippo (○) residents is presented (a). The average value of Kosugo residents is shown as a circle (b). Error bars show 1 standard deviation for each value. Calculated values, which are obtained by Eqs. (1) and (2), are described as solid and dotted lines, respectively. Neither a drop due to an accumulation of snow nor a faster reduction was observed in *H*p(10) for Kosugo residents (b).

^{137}Cs is observed after the thawing of snow (shown by dotted lines). The values of the half-lives of the rapid reductions in *H*p(10) were estimated to be 200–400 days according to Equation (2); these values are consistent with the corresponding half-lives in air dose rates. However, neither a drop due to the accumulation of snow nor a faster reduction was observed in the *H*p(10) values for Kosugo residents, and only the decrease that could be attributed to the radioactive decay of ^{134}Cs and ^{137}Cs was observed in this case (indicated by a solid line in Fig. 3 (b)). The main difference between the Marumori and Kosugo regions is their living environment. The former is a rural settlement, whereas the latter is a suburban city along a freeway. In our previous study[11)], we showed that the individual exposure dose depends on the indoor ambient dose equivalent rather than the outdoor ambient dose equivalent in each resident's dwelling. The discrepancy between the air dose rate and *H*p(10) for Kosugo residents might be caused by dose contributions from the fixed contamination in houses in the suburban environment of Kosugo. The effect of school and nursery, and community center yard decontamination on the *H*p(10) values for residents in Kosugo was not observed in the readings recorded in September. This is because a very limited area was decontaminated, and children mostly stayed at and around home, where no countermeasures were carried out, during preliminary-school broke for the summer.

Previously, we established the importance of accurately measuring *H*p(10) by the following two arguments: (1) doses measured using OSL dosemeters were markedly lower than those estimated by the gamma-ray survey method, and (2) the doses estimated using the environmental radiation level in the mesh survey conducted by the local government showed a large uncertainty because the distribution of the fallout was very patchy[11)]. The comprehensive results of this study further emphasize the importance of accurately measuring *H*p(10). For estimating individual doses in the future, *H*p(10) should be measured to prevent underestimation.

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