

# Chapter 19

## Reduction of External Exposure for Residents from the Fukushima Nuclear Accident by Weathering and Decontamination

Hiroko Yoshida

**Abstract** External exposure for residents resulting from the Fukushima nuclear accident was measured in the Marumori and Kosugo regions for the period from September 2011 to March 2013 after the occurrence of the Fukushima nuclear accident. Marumori is a rural settlement, and Kosugo is a suburban city along a freeway. The initial substantial reduction in personal dose equivalent [ $H_p(10)$ ] for Marumori residents, which was in accordance with the reduction in the air dose rate, was observed. Both values of the  $H_p(10)$  results and the air dose rates dropped and remained low during the heavy snow season. The values returned to previous levels and then followed a relatively faster reduction than the radioactive decay rate of  $^{134}\text{Cs}$  and  $^{137}\text{Cs}$  after the snow had thawed. These faster reductions are considered to be caused by weathering from snow melting or migration of radionuclides down the soil column. However, neither a drop resulting from an accumulation of snow nor faster reduction was observed in  $H_p(10)$  for Kosugo residents, except the reduction from the radiocesium decay, although the same reduction tendency as that in Marumori was observed in the air dose rates. 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. The effects of schoolyard decontamination on the  $H_p(10)$  values for schoolchildren in Kosugo have been observed in the readings recorded since October 2012, and dose reduction was evaluated as approximately 10–20  $\mu\text{Sv}/\text{month}$  on average.

**Keywords** Air dose rate • Decontamination • External exposure • Fukushima accident • Reduction • Residents • Weathering

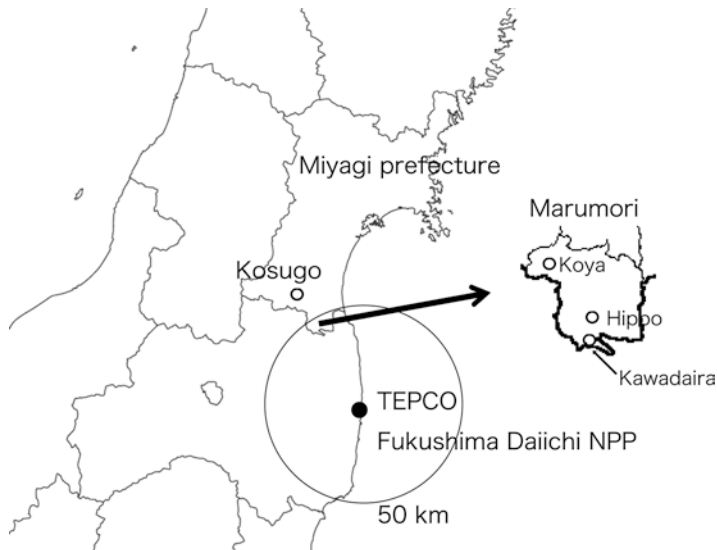
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## 19.1 Introduction

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 disaster 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 major 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 near the border between Miyagi and Fukushima. Marumori is located 46 km northwest of the NPP at the closest approach (Fig. 19.1). A distribution map of the radioactivity concentration in the soil [1] published by MEXT (Nuclear Regulation Authority after 1 April 2013) showed the presence of several radioactive plumes in this area, and the  $^{137}\text{Cs}$  deposition level ranged from 100 to 300 kBq/m<sup>2</sup>. After the decay of  $^{131}\text{I}$  (with a half-life of 8 days), radiation doses since June can be primarily attributed to Cs nuclides. When an initial substantial reduction in the air dose rate is observed, which is expected to occur as a result of 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. External exposure to radionuclides deposited in the environment was in many cases one of the dominant contributions to the total dose to the public after the accidental release of the radioactive material into the atmosphere. Internal exposure also contributed to the total dose. The main pathways of internal



**Fig. 19.1** Locations of Marumori and Kosugo. The territories studied in Marumori were geographically divided into three regions: Kawadaira, Hippo and Koya

exposure to residents were inhalation and ingestion. The environmental radioactivity level (fallout) [5] measured by the prefecture showed that the fallout ( $^{131}\text{I}$ ,  $^{134}\text{Cs}$ , and  $^{137}\text{Cs}$ ) was basically not detectable or that small amounts of radiocesium were sometimes detected in all prefectures including Fukushima from the end of June. Therefore, on 1 September 2011, when measurements were initiated, there was no longer a high possibility of being exposed to the source through inhalation.

In this study, the values of air dose rates (ambient dose equivalents [ $H^*(10)$ ]) in Marumori and Kosugo regions were analyzed to investigate their temporal variation from Cs nuclides. The personal dose equivalent [ $Hp(10)$ ] for residents in those regions was evaluated using optically stimulated luminescent (OSL) dosimeters. Then, the initial substantial reduction in personal dose for residents was compared with that in the air dose rate. The effect of school, nursery, and community center yard decontamination on the  $Hp(10)$  values for residents was evaluated. For area monitoring of penetrating radiation such as gamma rays emitted from Cs nuclides, the ambient dose equivalent [ $H^*(d)$ ], with  $d=10$  mm, which is written  $H^*(10)$ , is used as the operational quantity. The personal dose equivalent [ $Hp(d)$ ] is the dose equivalent in the International Commission on Radiation Units and Measurements (ICRU) tissue at a depth  $d$  in a human body below the position where an individual dosimeter is worn. For monitoring effective dose,  $d=10$  mm is recommended, and  $Hp(d)$  is written  $Hp(10)$ .

## 19.2 Methods

The  $Hp(10)$  for 54 Marumori and 71 Kosugo residents was evaluated starting 1 September 2011 and 16 December 2011, respectively, until the end of March 2013. The numbers of residents increased to 60 and 90 for Marumori and Kosugo residents after 31 August and 29 October 2012, respectively (150 in total). The residents mainly consisted of preliminary-school children and preschool children, and a few of them were the adults in their families. The territories in Marumori for which data were collected were geographically divided into three regions, Kawadaira, Hippo, and Koya, because the  $^{137}\text{Cs}$  deposition levels varied markedly in these regions [1]. The measurements were carried out using OSL personal dosimeters, and an OSL reader (InLight badge and microStar system; Nagase Landauer). In this study, readings were repeated three times. According to the specifications of the system, doses in excess of 100  $\mu\text{Sv}$  are measured within  $\pm 10\%$  standard deviation for an average value of three readings. Dosimeters were calibrated following the Japanese International Standard JIS Z 4511 [6]. The deviation in the energy-independent response for photons from 24 keV to 1.25 MeV is within  $\pm 10\%$ . The dosimeters 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 dosimeter was used by an individual, one by one, and read out approximately every 2 months (1.3–2.9 months) to obtain readings. The correct way to wear the OSL dosimeter was explained to the residents, and dosimeters were distributed to those

who were willing to wear the dosimeters 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 dosimeter correctly for the entire period of time that dosimeters were worn. The dosimeter 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 [7, 8] through the use of an NaI scintillation survey meter over the same period from September 2011 to March 2013, and the temporal variations in the rates from Cs nuclides after the decay of  $^{131}\text{I}$  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 [9], respectively, in Japan (from cosmic radiation and natural terrestrial radiation), were subtracted from each measured value.

## 19.3 Results and Discussion

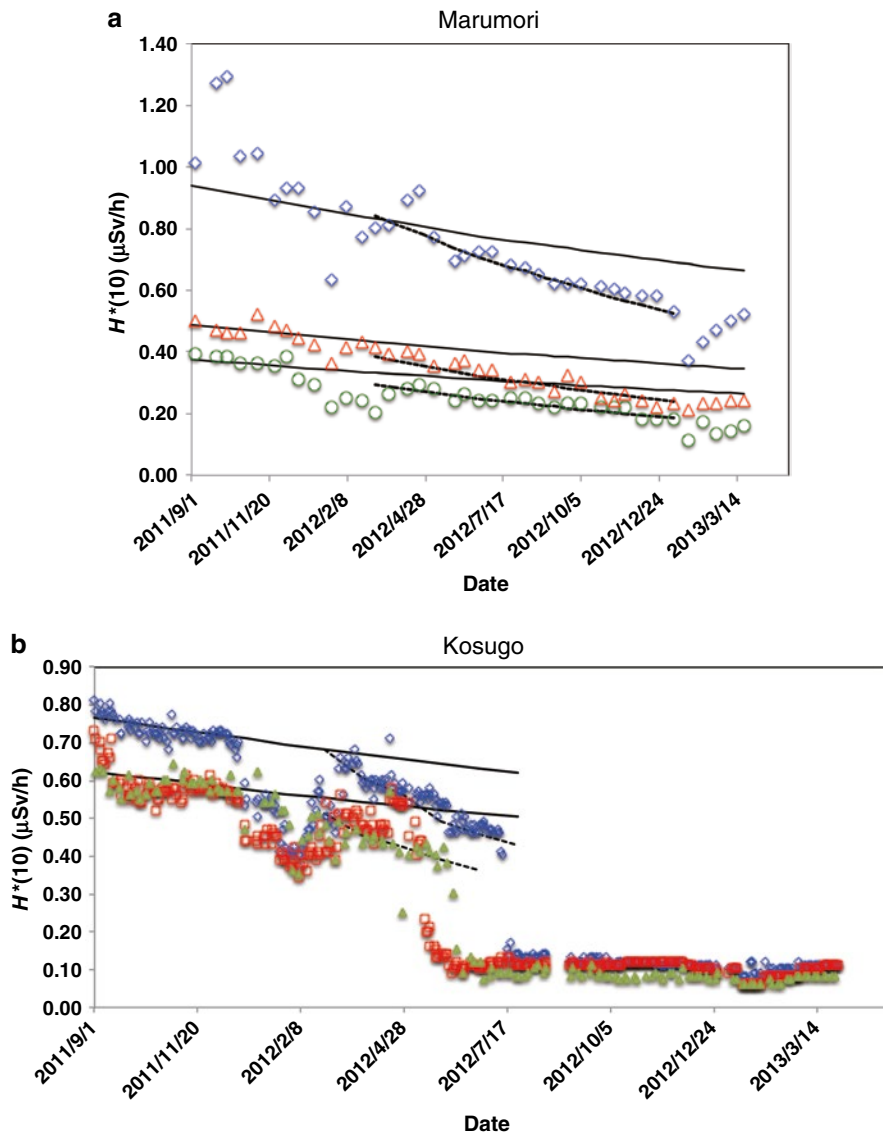
### 19.3.1 Air Dose Rates

In Fig. 19.2a, b, air dose rates (ambient dose equivalents [ $H^*(10)$ ]) from 1 September 2011 to the end of March 2013 in the Marumori and Kosugo regions are shown. The territories studied in Marumori were divided into three regions, Kawadaira, Hippo, and Koya (Fig. 19.1) as mentioned above. In Fig. 19.2a, the values in three measurement locations of Kawadaira (blue diamonds), Koya (red triangles), and Hippo (green circles) are shown. The three measurement locations shown in Fig. 19.2b are the Kosugo elementary school (blue diamonds), a nursery school (red squares), and a community center (closed green triangles). The symbols are used indicate measured  $H^*(10)$  values, and the calculated values obtained by Eq. (19.1) below are indicated by solid lines in the figures.

The air dose rate data were analyzed by comparing them with the calculated rates that accounted for the radioactive decay of  $^{134}\text{Cs}$  and  $^{137}\text{Cs}$ . The  $^{134}\text{Cs}/^{137}\text{Cs}$  activity ratio for Fukushima is close to 1 in most published data [10]. The effective doses  $E(t)$  were calculated using Eq. (19.1):

$$E(t) = E(0) / 3.7 \times \{2.7 \times \exp(-\lambda_1 t) + \exp(-\lambda_2 t)\}, \quad (19.1)$$

where  $\lambda_1$  and  $\lambda_2$  are the decay constants of  $^{134}\text{Cs}$  and  $^{137}\text{Cs}$ , respectively. From the effective dose rate constants of radionuclides, which are listed in the *Table of*



**Fig. 19.2** Air dose rates (ambient dose equivalents [ $H^*(10)$ ]) in Marumori (a) and Kosugo (b) regions. The values in three measurement locations of Kawadaira (blue diamonds), Koya (red triangles), and Hippo (green circles) are presented in a. Three measurement locations in b are the Kosugo elementary school (blue diamonds), a nursery school (red squares), and a community center (closed green triangles). Calculated values, which are obtained by Eqs. (19.1) and (19.2), are indicated by solid and dotted lines, respectively. A faster reduction than the radioactive decay of  $^{134}\text{Cs}$  and  $^{137}\text{Cs}$  appears after the thawing of snow in both regions

*Isotopes*, 10th edition [11], as 0.211 and 0.0779 for  $^{134}\text{Cs}$  and  $^{137}\text{Cs}$ , respectively, the proportion of  $^{134}\text{Cs}$  that contributed to the total effective dose was calculated to be 2.7 times higher than that of  $^{137}\text{Cs}$ . The value of  $E(0)$  was the measured value for each region, which represented the location factor. 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 factor [2].

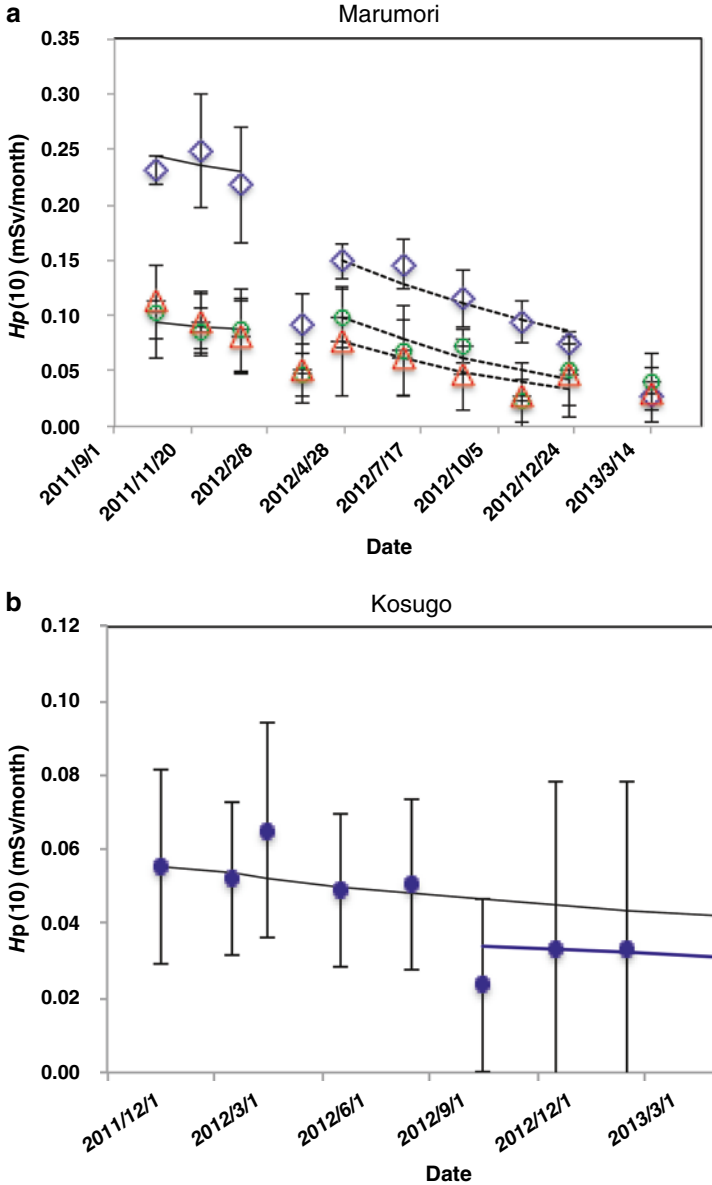
The data plotted in Fig. 19.2 show similar patterns until air dose rates dropped at the three measurement locations in Kosugo after decontamination (Fig. 19.2b). The observed long-term decrease in the plotted values is in accordance with the predicted radioactive decay process of  $^{134}\text{Cs}$  and  $^{137}\text{Cs}$  from summer 2011 to December 2011. 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  $^{134}\text{Cs}$  and  $^{137}\text{Cs}$ . This reduction is considered to be caused by weathering from snow melting or migration of radionuclides down the soil column [2–4]. 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; these were estimated as 450 and 300 days in Marumori and Kosugo, respectively, using Eq. (19.2):

$$E'(t) = E'(0) \times \exp(-\lambda_3 t), \quad (19.2)$$

where  $\lambda_3$  is the decay constant. Values calculated using Eq. (19.2) are shown using dotted lines in the figures. In Fig. 19.2b, all the air dose rate values dropped sharply between May and July 2012 because of the decontamination carried out for the yards of the elementary school, nursery school, and community center in Kosugo. In Marumori, decontamination of school and nursery yards was conducted in July 2011 but had not been carried out at the three measurement locations during the time measurements were being taken.

### 19.3.2 Personal Dose Equivalent for Residents

In Fig. 19.3 the  $H_p(10)$  of residents in Marumori and Kosugo regions are shown. The recorded  $H_p(10)$  values for approximately 2 months (1.3–2.9 months) were converted into monthly dose. In Fig. 19.3a, average values of  $H_p(10)$  for Kawadaira (blue diamonds), Koya (red triangles), and Hippo (green circles) residents are shown. The average values for Kosugo residents are indicated using circles in Fig. 19.3b. 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.



**Fig. 19.3**  $H_p(10)$  of residents in Marumori (a) and Kosugo (b) regions. Each average value of  $H_p(10)$  for Kawadaira (blue diamonds), Koya (red triangles), and Hippo (green circles) residents is presented in a. The average value of Kosugo residents is shown as a circle in b. Error bars show 1 standard deviation for each value. Calculated values, which are obtained by Eqs. (19.1) and (19.2), are described as solid and dotted lines, respectively. Neither a drop caused by an accumulation of snow nor a faster reduction, except decontamination of the schoolyard, was observed in  $H_p(10)$  for Kosugo residents in b

The  $H_p(10)$  of Marumori residents show a similar pattern to that observed in air dose rates: values drop during the heavy snow season, and faster reduction than the radioactive decay of  $^{134}\text{Cs}$  and  $^{137}\text{Cs}$  is observed after the thawing of snow (dotted line, Fig. 19.3a). The values of the half-lives of the rapid reductions in  $H_p(10)$  were estimated to be 200–400 days according to Eq. (19.2); these values are consistent with the corresponding half-lives in air dose rates. For Kosugo residents, neither a drop caused by the accumulation of snow nor a faster reduction was observed in the  $H_p(10)$  values, and only a decrease that could be attributed to the radioactive decay of  $^{134}\text{Cs}$  and  $^{137}\text{Cs}$  was observed (solid line, Fig. 19.3b), resulting in a slow decline in dose. The main difference between two 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 [12], 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. In Marumori, decontamination of school and nursery yards was conducted in July 2011 before  $H_p(10)$  measurements for residents were initiated. Thus, no reduction on  $H_p(10)$  values from the decontamination was observed in the readings during the measurements. In Kosugo, slow decontamination was carried out in July 2012, reducing the air dose rates in schoolyard from 0.46 to 0.19  $\mu\text{Sv/h}$  (Fig. 19.2b). Its effect on the  $H_p(10)$  values for residents (preliminary-school children) was not observed in the readings recorded in September [13], but have been observed since October 2012 after school summer holidays ended (Fig. 19.3b), and dose reduction was evaluated as approximately 10–20  $\mu\text{Sv/month}$  on average. Figure 19.3b also shows that the  $H_p(10)$  values for Kosugo residents have been declining in accordance with the radiocesium decay after decontamination as well.

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