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ARTICLE

A Preliminary Dose Assessment for the Population in an Area outside the 30 km Zone after the Fukushima Daiichi Nuclear Power Plant Accident

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For the purpose of planning of protective strategies after the Fukushima Daiichi nuclear power plant accident, it is important to evaluate external and internal doses to the public. However, the number of measured points and published measured data in contaminated areas are limited in the early phase of the accident. In the present study, potential dose levels to the public were assessed at a point in ”Deliberate Evacuation Area” during the period from March 15 to April 22 using available radiation monitoring data. External and internal doses from cloudshine, groundshine, inhalation and resuspension were estimated using cumulative doses, concentrations of soil samples and dust samples of radiation monitoring data. Mathematical models were also used to these doses in the case of the lack of monitoring data. Consequently, the effective dose to the public was estimated less than 28 mSv.

KEYWORDS: Fukushima Daiichi nuclear power plant accident, radiation monitoring, dose, radioiodine, radiocesium

I. Introduction

On March 11, 2011, natural disasters initiated the Fukushima Daiichi nuclear power plant accident. The accident resulted in a release of radioactivity to the environment and a wide range of radioactive contamination.

Repeated earthquake and loss of electricity prevented the local government from operation of emergency environmental radiation monitoring program right after the accident. Measurements started on March 15 in the area over 20 km radius around the plant. Relatively high dose rate was detected at distances even over 30 km, in directions of north to northwest from the plant. It is considered that the radioactive contamination in the northwest area occurred on March 15-16[1)].

The residents within a 20 km radius from the plant were directed to evacuate on March 12. As well, staying indoors was recommended to the residents within 20-30 km area from the plant on March 15[1)]. However, these protective actions were not implemented for the residents over a 30 km radius in the early phase of the accident. On April 11, the area over 30 km in directions of north to northwest from the plant was established as “Deliberate Evacuation Area”[1)] which has the possibility of accumulated dose reaching 20 mSv within one year after the accident. Since the criterion for long-term protective actions had not been developed in Japan, the dose level of 20 mSv was selected from the ICRP’s band of reference levels for emergency exposure situations[2)]. On April 22, the residents in the area were directed to evacuate within about a month.

In order to consider the effectiveness of protective action strategies, it is important to evaluate external and internal doses to the public. However, the number of measured points and monitoring data in contaminated areas are limited in the early phase of the accident. In the present study, potential dose levels to the public were assessed at a point in ”Deliberate Evacuation Area” from March 15 to April 22, i.e., the period from the passage of the plume to the evacuation of the residents in the area using available radiation monitoring data provided by regulatory authorities.

II. Data

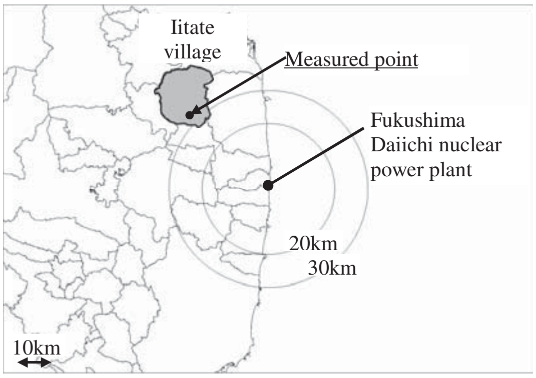

Fig. 1 The area around the Fukushima Daiichi nuclear power plant.

Figure 1 shows the area around the Fukushima Daiichi nuclear power plant. This study assessed the received doses at the measured point shown in **Fig. 1** because the number of radiation monitoring data in the point was larger than that in other points in ”Deliberate Evacuation Area”. These measured data would be available to estimate received dose more accurately. The measured point is at 33 km northwest from the plant and in Iitate village.

The release of radioactivity to the environment and radioactive contamination has caused radiation exposures to

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the public from different exposure pathways. In the study, the received doses were assessed from the following exposure pathways in the early phase of the accident.

- Exposure to external irradiation from the passing plume (cloudshine).
- Exposure to external irradiation from deposited radionuclides (groundshine).
- Internal irradiation by radionuclides incorporated by the inhalation of contaminated air from the passing plume (inhalation).
- Internal irradiation after inhalation of resuspended radionuclides, which were once deposited on the ground (resuspension).

Received doses from these pathways can be assessed on the basis of measurements of air concentration, ground contamination, or radiation fields resulting from these releases. However, this was not always possible in the study. Mathematical models were also used to estimate the impact of radionuclides released to the atmosphere.

In the study, the available radiation monitoring data at the measured point were cumulative doses, radionuclide concentrations in soil samples and also in atmospheric dust samples. The detail of these measured data is as follows.

(1) Cumulative doses

Figure 2 shows cumulative doses at the measured point[3] from March 24 to April 22 and dose rates per day derived by cumulative doses. Dose rates per day were very high at the beginning of the measurement. Then, it gradually decreased and was almost constant value after one month.

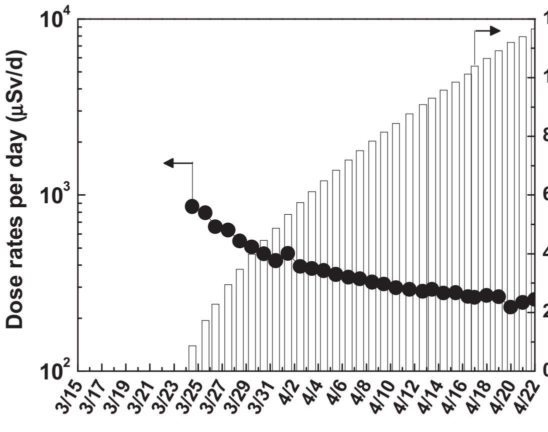

Fig. 2 Cumulative doses at the measured point.

(2) Soil samples

Soil samples were collected at the measured point from March 23. **Figure 3** shows the concentrations of ^{131}I, ^{134}Cs and ^{137}Cs in the samples[4]. The concentration of ^{131}I gradually decreased after March 23.

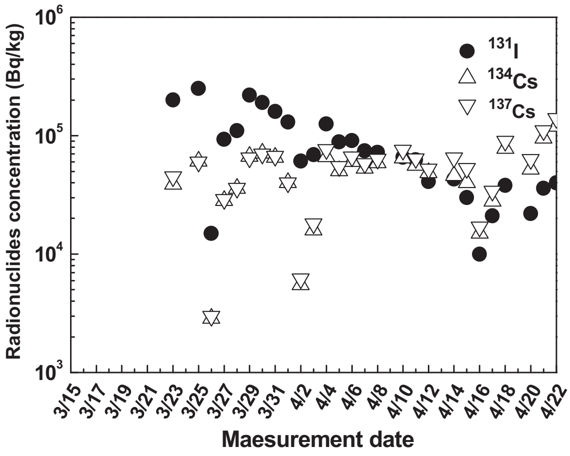

Fig. 3 Concentration of radionuclides in soil sample.

(3) Atmospheric dust samples

Atmospheric dust samples were collected at the measured point several times a day from March 24 to 29. **Figure 4** shows the maximum concentrations of ^{131}I, ^{134}Cs, ^{137}Cs, ^{132}Te and ^{132}I in the samples[5]. The concentrations of ^{134}Cs and ^{137}Cs on March 24, and ^{134}Cs on March 29 were below detection limits.

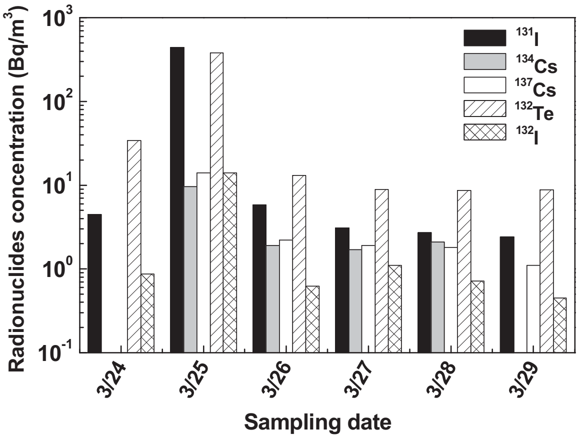

Fig. 4 Concentration of radionuclides in atmospheric dust sample.

III. Methods

Figure 5 shows gamma dose rates at the government office in Iitate village and precipitation intensities in this area from March 15 to 17. It was found that gamma dose rates at the government office in Iitate village were increased rapidly from 16:00 on March 15 and then the dose rates were almost not decreased after approximately 18:20 on March 15[6]. On the other hand, it rained in Iitate village from the evening on March 15 to the morning on March 16[7]. Therefore, it is considered that the radioactive plume would pass through the measured point in the evening on March 15 and the wet deposition process mainly caused the contamination of the ground.

Unfortunately there were no measurements for concentrations of radionuclides in air during this plume passage. Therefore, the time integrated air concentrations of each radionuclide were derived from the measured concentrations of soil samples, assuming that the wet deposition mainly caused the contamination of the ground. Then, both cloudshine and inhalation doses during the passing plume were calculated using the estimated concentrations of radionuclides in the air. The received doses due to groundshine and resuspension after March 16 were estimated using the measured data for cumulative doses and the concentration of atmospheric dust samples.

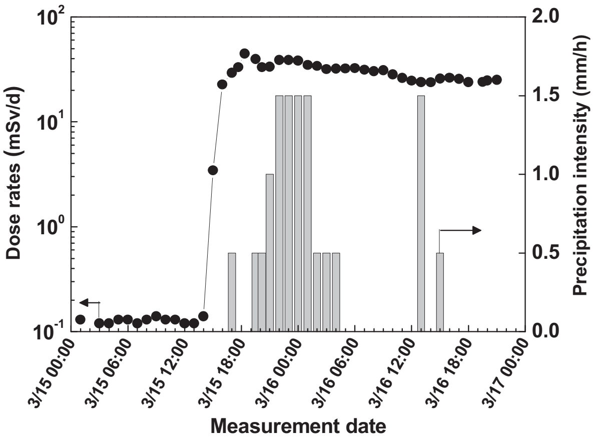

Fig. 5 Dose rates in Iitate village from March 15.

1. Evaluation of external and internal doses from the passing plume

The contamination of the ground was mainly caused by the wet deposition of radionuclides from the plume. In the study of Brenk *et al*[8], washout deposition is calculated by [9]

$$W_i = \int W\, dt = \omega \int 10^{-3} I \overline{\chi_\iota}\, dt, \tag{1}$$

where

W_i= concentration of radionuclide i on the ground (Bq/m^2)
W = washout deposition rate (Bq/m^2·h)
ω = washout ratio
I = precipitation intensity (mm/h)
$\overline{\chi_\iota}$ = time-integrated concentration of radionuclide i in air (Bq·h/m^3)

The time-integrated concentrations of radionuclides in air were derived from Eq. (1). Concentration of the radionuclides on the ground was derived by multiplying concentration of the radionuclides in soil samples of 5 cm depth by soil density (= 65 kg/m^2). It was assumed that the wet deposition mainly caused the contamination of the ground during the plume passage between 16:00 to 19:00 on March 15. The precipitation intensity during this period was 0.5 mm/h based on meteorological data at Iitate village. The washout ratio was assumed to be 3.0×10^5 of the washout data for aerosols[8].

External and internal doses from the passing plume were evaluated using derived time-integrated concentration of radionuclides in air as follows.

(1) External exposures due to cloudshine

The effective dose, E_{cloud}(i), and the equivalent dose to the thyroid, $H_{\text{thy,cloud}}$(i), due to irradiation from radionuclide i were estimated by

$$E_{\text{cloud}}(\text{i}) = \overline{\chi_\iota} \times F_{\text{air,i}}, \tag{2}$$

$$H_{\text{thy,cloud}}(\text{i}) = \overline{\chi_\iota} \times F_{\text{air,i}}, \tag{3}$$

where

$\overline{\chi_\iota}$: time-integrated concentration of radionuclide i in air (Bq·h/m^3)
$F_{\text{air,i}}$: dose coefficients for air submersion for radionuclide i for the effective dose or thyroid dose (Sv/Bq·h/m^3)[10]

(2) Internal exposures due to inhalation

The effective dose, E_{inh}(i), and the equivalent dose to the thyroid for adult and child (1-year-old child), $H_{\text{thy,inh}}$(i), due to inhalation of radionuclide i were estimated by

$$E_{\text{inh}}(\text{i}) = C_{\text{a,i}} \times B \times F_{\text{inh,i}}, \tag{4}$$

$$H_{\text{thy,inh}}(\text{i}) = C_{\text{a,i}} \times B \times F_{\text{inh,i}}, \tag{5}$$

where

$C_{\text{a,i}}$: time-integrated concentration of radionuclide i in air (Bq·h/m^3)
B: breathing rate for adult or child (m^3/h)[11]
$F_{\text{Inh,i}}$: inhalation dose coefficient for radionuclide i for the effective dose or thyroid dose (Sv/Bq)[11]

2. Evaluation of external and internal doses from deposited radionuclides

(1) External exposures due to groundshine

The evaluation of external doses due to groundshine was needed to estimate dose rates per day before March 23. Dose rates per day from March 16 to 23 were estimated by fitting an exponential model. The model is shown by

$$y = y_0 + \text{A}e^{-\lambda t}, \tag{6}$$

where

y = dose rates per day (μSv/d)
y_0 and A = constant (μSv/d)
λ = decay constant (=0.693/$t_{1/2}$)
$t_{1/2}$ = half - life of radionuclide (d)
t = elapsed time from March 16 (d)

For the days from March 24 to April 22, dose rates per day shown in **Figure 2** were fitted with the above model in consideration of the difference of decay constants between radioiodine and radiocesium. Then, external doses were estimated by summing the dose rates per day extrapolated by Eq. (6) from March 16 to 23, and the dose rates derived by cumulative doses from March 24 to April 22.

(2) Internal exposures due to resuspension

The number of atmospheric dust samples was limited at the measured point from March 24 to 29. These measured data are considered due to resuspension.

In the present study, it was assumed the residents inhaled the concentrations of radionuclides for a day. The effective dose, E_{res}(i), and the equivalent dose to the thyroid for adult and child (1-year-old child), $H_{\text{thy,res}}$(i), due to resuspension of radionuclide i were estimated by

$$E_{\text{res}}(\text{i}) = C_{\text{d,i}} \times B \times F_{\text{inh,i}}, \tag{7}$$

$$H_{\text{res,inh}}(\text{i}) = C_{\text{d,i}} \times B \times F_{\text{inh,i}}, \tag{8}$$

where

$C_{\text{d,i}}$: time-integrated concentration of radionuclide i in dust sample (Bq·d/m^3) (**Figure 4**)
B: breathing rate for adult or child (m^3/d)[11]
$F_{\text{inh,i}}$: inhalation dose coefficient for radionuclide i for the effective dose or thyroid dose (Sv/Bq)[11]

IV. Results and Discussion

1. Evaluation of external and internal doses from the passing plume

Firstly, the concentrations of radionuclides in soil for the passage period of the plume, in the evening on March 15, were estimated using the measured data in soil samples. **Figure 6** shows the result from the estimation of the concentration of ^{131}I in soil extrapolated from measured data of soil samples. That of ^{134}Cs and ^{137}Cs was estimated based on the measured data on March 23.

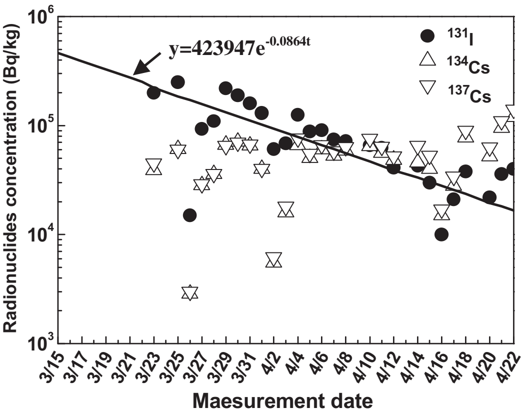

Fig. 6 Concentration of radioiodine and radiocesium in soil samples.

Additionally, it is important to consider the presence of short-lived radionuclides for the assessment of received doses at the early phase of the accident[12)]. For example, ^{132}Te and ^{132}I were detected in the northwest area from the plant on March 15 and 16[13)]. In the present study, the concentration of ^{132}Te in soil was derived from that of ^{131}I and the estimated composition ratio (^{131}I : ^{132}Te = 0.93 : 1.00), with the decay of radionuclides considered, from the measured data in Magata settlement[14)]. The concentration of ^{132}I was derived from that of ^{132}Te assuming radioactive equilibriums. In the study, external and internal doses for ^{131}I ^{134}Cs, ^{137}Cs, ^{132}Te and ^{132}I were evaluated because the contributions of these radionuclides to received doses would dominate at the early phase of the accident[12)]. The external doses for radioactive noble gases due to cloudshine were excluded because of the lack of measured data.

Next, the concentrations of radionuclides in the air were estimated using the concentrations of these radionuclides in soil and Eq. (1). **Table 1** shows the result from the estimation of the time-integrated concentrations of radionuclides in air.

The external and internal doses from the passing plume were assessed using the time-integrated concentrations of radionuclides in air.

Table 1 Time-integrated concentration of radionuclides in air (Bq·h/m^3).

^{131}I	^{134}Cs	^{137}Cs	^{132}Te	^{132}I
1.9×10^5	1.7×10^4	2.0×10^4	2.0×10^5	2.1×10^5

(1) External exposures due to cloudshine

Effective dose to irradiation from the passing plume was estimated to be approximately 0.1 mSv. The dose contributions from ^{132}I and ^{131}I were 77% and 11% in total, respectively. External exposures due to radioactive noble gases were not estimated due to lack of the measured data.

(2) Internal exposures due to inhalation

Figure 7 shows the results from the evaluation of internal dose due to inhalation of radionuclides. The effective dose was estimated to be 2.5 and 5.0 mSv for an adult and a child, respectively. The equivalent doses to the thyroid were 41.0 mSv for adults and 91.5 mSv for children. Radionuclide of ^{131}I and ^{132}Te contributed largely to the inhalation dose. These doses were estimated to be large if residents spent all times outdoors for the passage period of the plume.

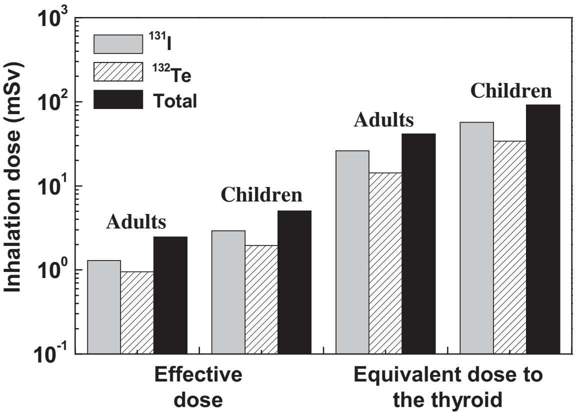

Fig. 7 Internal doses due to inhalation of radionuclides.

2. Evaluation of external and internal doses from deposited radionuclides

(1) External exposures due to groundshine

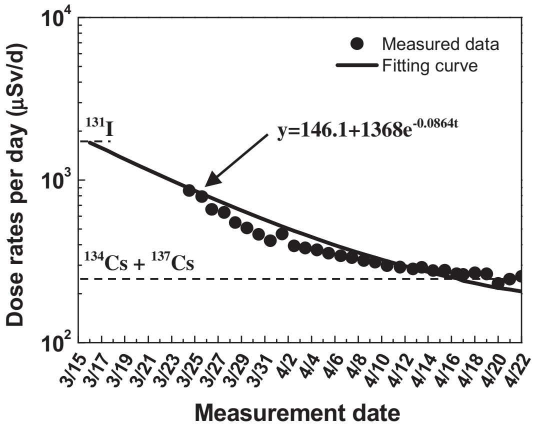

Fig. 8 Evaluation of cumulative doses by using the exponential model.

Figure 8 shows the results from the evaluation of dose rates per day by using the exponential model. It is assumed that the decrease of dose rates per day was mainly due to the decay of ^{131}I and the exponential model for ^{131}I was fitted to cumulative doses measured per day. The half - life of ^{131}I is 8.02 d. Eq. (6) becomes:

$$y = y_0 + \mathrm{A}e^{-0.0864t}, \tag{9}$$

Fitting to the measured data yielded, the values of y_0 and A were derived. As a result, Eq. (9) is:

$$y = 146.1 + 1368e^{-0.0864t}, \tag{10}$$

Using Eq. (10), the dose rates was estimated to be approximately 1.7 mSv/d at 0:00 a.m. on March 16.

Additionally, the study estimated the dose rates for radioiodine, ^{131}I, and for radiocesium, ^{134}Cs and ^{137}Cs, from the dose rates on March 16 derived by Eq. (10). Assumptions made in this study are as follows. The estimated doses were dominated by radioiodine, ^{131}I, and radiocesium, ^{134}Cs and ^{137}Cs. Dose rates for ^{131}I decreased rapidly for the first month after the accident. On the other hand, dose rates for ^{134}Cs and ^{137}Cs were almost constant for the period because these radiocesium have long half-life. It is considered that dose rates after one month of the accident were mostly dominated by ^{134}Cs and ^{137}Cs. Therefore, dose rates for these radiocesium could be estimated based on measured data on April 22 and were almost constant values for the first month after the accident. As a result, the dose rate for ^{134}Cs and ^{137}Cs on March 16 could be estimated at 0.25 mSv/d. On the other hand, the estimated dose rate for ^{131}I was at approximately 1.45 mSv/d.

The external dose was estimated at approximately 23.5 mSv by summing the dose rates from March 16 to April 22. It consisted of ^{131}I (13.6 mSv) and ^{134}Cs and ^{137}Cs (9.9 mSv), in the first month after the accident.

Meanwhile there were some available data of integrated dose measured with dosimeters placed in the area of interest. The dose rates derived from these data were much higher than the estimated one before March 17. It is considered that the dosimeter data included dose rates for other radionuclides, especially short-lived radionuclides such as ^{132}Te and ^{132}I. As described before, the concentration of ^{132}Te in soil was derived from that of ^{131}I and the estimated composition ratio, with the decay of radionuclides considered, from the measured data in Magata settlement[14]. The concentration of ^{132}I was derived from that of ^{132}Te assuming radioactive equilibriums. The dose rates of ^{132}Te and ^{132}I were estimated by the dose rates of ^{131}I, the estimated composition ratio and dose coefficients for exposure to contaminated ground surface[10].

As a result, the dose rates from ^{132}Te and ^{132}I on March 16 were estimated to be 0.95 and 9.4 mSv/d, respectively. It was found that these radionuclides with half-lives shorter than ^{131}I caused higher doses at the early phase of the accident. Cumulative doses from ^{132}Te and ^{132}I from March 16 to April 22 were 3.9 and 9.7 mSv, respectively. It was found that effective doses from groundshine were estimated at 37.1 mSv.

The resulting total effective doses from groundshine were 37.1 mSv if residents spent all times outdoors. However, evaluation of the external doses needed to take the shielding effect of building into account. The NSC's guideline provides the sheltering factor of 0.4 for a typical Japanese house and 1.0 for outdoors[15]. If the inhabitants spend 16 hours in a house and 8 hours outdoor, the weighted sheltering factor becomes 0.6. Consequently, the corrected external dose from groundshine actually was 22.3 mSv from March 16 to April 22.

(2) Internal exposures due to resuspension

Figure 9 shows the results from the evaluation of internal doses due to resuspension of ^{131}I, ^{134}Cs, ^{137}Cs, ^{132}Te and ^{132}I. Radioiodine of ^{131}I contributed largely to internal doses. The estimated effective doses were 0.1 and 0.2 mSv for adults and for children, respectively. The equivalent doses to the thyroid were estimated at 1.5 mSv for adults and 3.3 mSv for children.

Internal doses due to resuspension would be underestimated because we used the measured data of atmospheric dust samples from March 24 to 29. However, implication of the potential underestimation may be insignificant because the estimated dose due to resuspension might be much smaller than that due to inhalation.

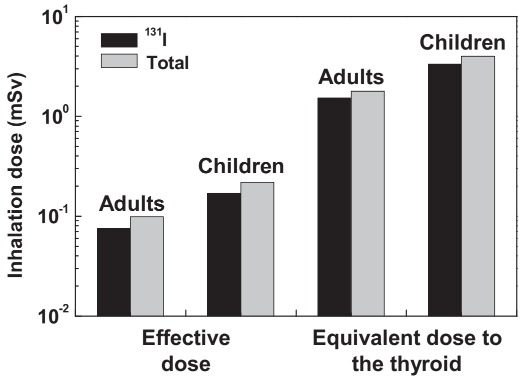

Fig. 9 Internal dose due to resuspension of radionuclides.

(3) Total doses

Table 2 shows the results from the evaluation of potential dose levels for exposure to the public due to cloudshine, groundshine, inhalation and resuspension from March 15 to April 22. The total effective doses were 25.0 mSv for adults and 27.6 mSv for children. It should be noted that the exposures from cloudshine and inhalation already terminated at the time of this assessment and most of the doses results from the groundshine which are persistent without remedial actions. The most important implication of this assessment is that the groundshine dose evaluated only for around one month exceed the tentative evacuation criteria set by the government. It means that an immediate protective strategy should be considered for the population in Iitate area for which doses were assessed in this study.

Table 2 The results from the evaluation of effective dose.

	External doses (mSv)		Internal doses (mSv)		Effective dose (mSv)
	cloudshine	groundshine	inhalation	resuspension	
Adult	0.1	22.3	2.5	0.1	25.0
Child			5.0	0.2	27.6

V. Conclusions

In order to assess the potential dose levels to the residents at a location in ”Deliberate Evacuation Area” for the period from the passage of the plume to the evacuation of the residents in the area, external and internal doses from cloudshine, groundshine, inhalation and resuspension were estimated using available radiation monitoring data. Mathematical models were also used to compensate the lack of measured data.

Doses due to cloudshine and inhalation were estimated using the concentration of radionuclides in air derived from the data of soil samples and precipitation intensity. External doses due to groundshine were evaluated for the period from March 16 to April 22 by integrating dose rates derived both from estimated and measured data. The dose rates from March 16 to 23 were estimated by fitting an exponential model to the measured data.

The total effective dose to the public was estimated less than 28 mSv from March 15 to April 22, considering the effect of staying indoors for external doses. It is important to consider the presence of short-lived nuclides such as ^{132}Te and ^{132}I for the assessment of received doses in the early phase of the accident. The estimated doses would be over 20 mSv which is the criterion for evacuation as established by authorities. It is considered that the protective action strategy should be implemented immediately after April 11, though there would be a need to of operational considerations in implementing planned protection strategies by the local governments$^{1)}$.

Since the assessment in this study is very preliminary and is subject to significant uncertainty due to limited data at the time of study. However, the uncertainty would not alter the important conclusion that a protective strategy is needed for the population in the area considered in this study because the dominating exposure pathway, groundshine, should persist without adequate remedial actions.

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