Assessment of radiation doses to the public in areas contaminated by the Fukushima Daiichi Nuclear Power Station accident

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In the areas contaminated by radioactive materials due to the Fukushima Daiichi Nuclear Power Station accident, many residents are exposed to radiation through various exposure pathways. Dose assessment is important for providing appropriate protection to the people and clarifying the impact of the accident. The aim of this study is to provide preliminary results of the assessment of radiation doses received by the inhabitants of Fukushima Prefecture. To assess the doses realistically and comprehensively, a probabilistic approach was adopted using data that reflected realistic environmental trends and lifestyle habits in Fukushima Prefecture. In the first year after the contamination, the 95th percentile of the annual effective dose received by the inhabitants evacuated from the evacuation areas and the deliberate evacuation areas was mainly in the 1–10 mSv dose band. However, the 95th percentile of the dose received by some outdoor workers and inhabitants evacuated from highly contaminated areas was in the 10–50 mSv dose band. The doses due to external exposure to deposited radionuclides were the dominant exposure pathway, and their contributions were about 90% under prevailing contamination conditions in Fukushima Prefecture. In addition, 20%–30% of the lifetime effective dose was delivered during the first year after the contamination.

Key Words: *dose assessment, probabilistic approach, measurement data, exposure pathways*

1. Introduction

After the Great East Japan Earthquake, large tsunamis struck the Fukushima Daiichi Nuclear Power Station, which led to a nuclear accident that released a large amount of radioactive materials into the environment[1]. In the areas contaminated as a result of the accident, many residents are now being exposed to radiation through various exposure pathways in their daily lives. To protect people and manage the exposure situation appropriately, a suitable dose assessment is necessary[2]. The aim of this study is to provide preliminary results of the assessment of radiation doses received by the inhabitants of Fukushima Prefecture. This assessment is intended to be realistic and comprehensive. For this purpose, the doses are assessed by a probabilistic approach based on environmental monitoring data reflecting realistic lifestyle habits in Fukushima Prefecture.

2. Method

(1) Scope

In the early phase of the accident, inhabitants were evacuated to prevent and reduce radiation exposure. The National Institute of Radiological Sciences (NIRS) suggested

18 evacuation scenarios according to the Fukushima Health Management Survey[3)]. These scenarios are listed in **Table 1**. Doses were assessed for the 18 evacuation scenarios suggested as well as for the inhabitants who continued to live in Fukushima City, Koriyama City, and Iwaki City after the contamination occurred. The total effective doses were calculated as the summation of those received in the municipalities listed in each evacuation scenario. The present study assumed that other protective actions such as sheltering and stable iodine uptake were not implemented.

The dosimetric endpoints of the study are the effective doses received by adults in the first year after the contamination and over the inhabitants' lifetimes[1]. Radiation exposure occurs through several pathways. The present study assessed the doses due to external exposure to radionuclides deposited on the ground (hereafter referred to as groundshine) and to radionuclides in the radioactive cloud (hereafter referred to as cloudshine) as well as the doses due to internal exposure through inhalation of radionuclides in the radioactive cloud.

The doses due to inhalation of noble gases and radioactive materials resuspended from the ground surface were not included in the assessments. This assumption was adopted according to a World Health Organization (WHO) report[2)]. It mentions that inhalation of noble gases and radioactive materials resuspended are not expected to provide a significant contribution to radiation exposure. Also the doses due to cloudshine caused by noble gases cannot be considered in the present study (see 2(2)b)).

(2) Models for assessing doses due to external and internal exposures

a) External exposure to deposited radionuclides

The effective dose received by population group j from groundshine E_j^{gd} in each municipality listed in the evacuation scenarios is represented by

$$E_j^{\mathrm{gd}} = \sum_l \left\{ \int f_l(t) \cdot \left\{ s_g \cdot p_{l,in,j} + p_{l,out,j} \right\} \cdot \dot{E}_v^{\mathrm{gd}}(t)\, dt \right\}, \qquad (1)$$

where

j	Index for population types
l	Index for location types
$\dot{E}_v^{gd}(t)$	Effective dose rate from groundshine at locations of virgin land in the urban environment
$f_l(t)$	Location factor for urban locations of type l,
$p_{l,in\,(\mathrm{or}\,out),j}$	Ratio of time spent indoors (or outdoors) at location type l to that of the assessment period
s_{gd}	Shielding factor for groundshine

The index l for location types represents virgin land, dirt surfaces, and asphalt, which are classified according to the characteristics of the ground surface[4-6)]. The location factors are defined by dividing the dose rates at a given location by those at an open undisturbed field[4-6)]. The location factors are represented as a function of the time elapsed after the contamination, as follows:

$$f_l(t) = a_{l,1} \cdot \exp\left(-\frac{\ln 2}{T_l} \cdot t\right) + a_{l,2}, \qquad (2)$$

where $a_{l,1}$, $a_{l,2}$, and T_l are fitting parameters for the location factors of cesium. The values of these parameters are listed in **Table 2**; they were determined from the data obtained from the Chernobyl accident[6)].

The calculations were performed for three population groups: indoor workers, outdoor workers, and pensioners. The ratio of time spent at location type l for the assessment period was defined as a fraction of the average time spent in a day at location l, as follows:

$$p_{l,in(\mathrm{or}\;out),j} = \frac{t_{l,in(\mathrm{or}\;out),j}}{24}, \qquad (3)$$

where $t_{l,in(\mathrm{or}\;out),j}$ is the time spent indoors (or outdoors) in a day at location l by an individual of population group j. The values of $t_{l,in(\mathrm{or}\;out),j}$ were determined by generating random numbers in accordance with the probabilistic distribution functions obtained from the surveys in Fukushima Prefecture[2]. The statistical values to determine the probabilistic distribution functions of $t_{l,in(\mathrm{or}\;out),j}$ are listed in **Table 3**. Random numbers were generated 10,000 times using the global sensitivity analysis code GSALab[8)], which was developed by the Japan Atomic Energy Agency (JAEA).

The assessments were performed with the assumption that indoor workers and pensioners spend all day in urban areas paved with asphalt. However, it is assumed that outdoor workers spend their working hours in areas classified as dirt

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1 The integrated period is 60 years for adults.

2 The surveys have been conducted in cooperation with Fukushima City office, Northern Fukusima affiliate of Contractors Association, Japan Agricultural Cooperatives and Senior Citizens Club of Fukushima City. Pensioners consist of the members of Senior Citizens Club of Fukushima City. They spend the most time of a day at inside of their house. More information can be found Takahara et al. (2012)[7)]. In the present work, data surveyed for the month of February, March, and April 2011 were used.

surfaces in urban environment. In the present study, the doses assessed for the population living in urban environment, such as Fukushima City and Koriyama City, whereas rural environment prevails in some municipalities in Fukushima Prefecture. Further assessments will be needed taking into account both urban and rural environment.

The shielding factor s_{gd} for gamma radiation from deposited radionuclides is defined as the ratio of ambient doses inside a house to those outside. The assessments were performed using a shielding factor s_{gd} of 0.3 based on the dosimetric survey conducted in Fukushima Prefecture[3].

The effective dose rate from groundshine at locations of virgin land is given by the following form:

$$\dot{E}_v^{gd}(t) = r(t) \sum_i \{k_{gd,i} \cdot C_i \cdot A_{Cs137}(0) \cdot \exp(-\lambda_i \cdot t)\}, \quad (4)$$

where

- $r(t)$ Attenuation function of dose rate due to migration of ^{137}Cs into the soil
- C_i Ratio of the surface activity density of radionuclide i to that of ^{137}Cs
- $A_{Cs137}(0)$ Initial value of the surface activity density of ^{137}Cs
- λ_i Decay constant for radionuclide i
- $k_{gd,i}$ Effective dose coefficient from surface density activity

The attenuation function $r(t)$ is given by the following equation[2, 4-6, 9]:

$$r(t) = p_1 \cdot \exp\left(-\frac{\ln 2}{T_1} \cdot t\right) + p_2 \cdot \exp\left(-\frac{\ln 2}{T_2} \cdot t\right), \quad (5)$$

The parameter values were $p_1 = 0.34$, $p_2 = 0.66$, $T_1 = 1.5$ years, and $T_2 = 50$ years[2,9].

Radioactive fallout and contamination in most of the contaminated areas of Fukushima Prefecture were estimated to have occurred on March 15 or 16, 2011. This is because the gamma dose rate in air suddenly increased over the background radiation rates during these days[10]. In the present study, the doses were assessed with the assumption that the contamination occurred at 0:00 on March 15, 2011[4].

The ratio of the surface activity density of each radionuclide i to that of ^{137}Cs was determined according to a report of WHO[2]. The relative isotopic composition of deposited radionuclides is listed in **Table 4**.

Equation (4) was calculated using values of $A_{Cs137}(0)$ produced by the random number generator according to the distributions of the measured surface density of ^{137}Cs for each municipality listed in the evacuation scenarios.

The distributions of the surface activity density of ^{137}Cs on March 15, 2011 were derived from the monitoring data measured by the national authority of Japan (MEXT[5])[11]. The soil samples were collected from a 5-cm surface layer within 80 km of the Fukushima Daiichi Nuclear Power Station[6]. In principle, the measurements were conducted at a single location per 2 × 2 km^2 grid for these areas. The details of the surface density of ^{137}Cs are discussed in section 2(3).

The effective dose coefficients were obtained from a U.S. Environmental Protection Agency (EPA) report[13].

b) External exposure to the radioactive cloud

The effective dose received by population group j due to cloudshine E_j^{cd} is represented by

$$E_j^{cd} = p_{in,j} \cdot s_{cd} \cdot E_{out}^{cd} + p_{out,j} \cdot E_{out}^{cd}, \quad (6)$$

where

- $p_{in,j}$ Ratio of time spent indoors
- $p_{out,j}$ Ratio of time spent outdoors
- E_{out}^{cd} Effective dose due to cloudshine outdoors
- s_{cd} Shielding factor for cloudshine due to radionuclides in the radioactive cloud

The ratio of time spent indoors or outdoors was calculated as the total time spent indoors or outdoors in various locations per day. To calculate the external doses due to the radioactive cloud, E_{out}^{cd}, it was necessary to convert the surface density of radionuclides to time-integrated activity concentrations in air. Noble gases, which do not deposit on the ground surfaces, were not included in the assessments.

The effective dose due to cloudshine outdoors, E_{out}^{cd}, is represented as follows:

$$E_{out}^{cd} = \sum_i \left(\frac{C_i \cdot A_{Cs137}(0)}{V_i}\right) \cdot k_{cd,i}, \quad (7)$$

[3] The dosimetric surveys were made for 215 households in Fukushima Prefecture. The breakdown of building types is as follows. 1- or 2-story wood frame houses: 194, 1-story concrete houses: 5, and concrete houses with 2 or more stories: 16[7].

[4] The data presented in this paper used Japan Time [i.e., Greenwich Mean Time (GMT) plus 9 h].

[5] MEXT is the abbreviation for the Ministry of Education, Culture, Sports, Science and Technology of Japan.

[6] The soil samples had been collected prior to the rainy season in Japan, from June 6 to June 14 and from June 27 to July 8, 2011, so that the level of contamination could be observed before any changes occurred on the soil surface [12].

where

V_i Bulk deposition velocity of radionuclide i

$k_{cd,i}$ Effective dose coefficients for air submersion of radionuclide i

The deposition velocity V_i is determined according to the method in the WHO preliminary report[2)]. The areas in which the surface density of ^{137}Cs, A_{Cs137}, is higher than or equal to 30 kBq m^{-2} were treated as being contaminated through wet deposition, with deposition velocities of $V_{I\text{-}131}$ = 0.07 m s^{-1} for ^{131}I and V_{other} = 0.01 m s^{-1} for other radionuclides. If the surface density A_{Cs137} is less than 30 kBq m^{-2}, then the contamination originated from dry deposition with deposition velocities of $V_{I\text{-}131}$ = 0.01 m s^{-1} for ^{131}I and V_{other} = 0.001 m s^{-1} for other radionuclides. The doses due to cloudshine and inhalation were calculated using the surface densities of ^{137}Cs in the municipality where the inhabitants stayed while the radioactive plumes passed.

The value of 0.6 was used as the shielding factor s_{cd} for gamma radiation from the radioactive plume[14)]. The effective dose coefficients $k_{cd,i}$ were obtained from an EPA report[13)].

c) Internal exposure through inhalation of radionuclides

The effective dose received by the population group j from internal exposure through inhalation of radionuclide i in the radioactive cloud E_j^{inh} is represented by

$$E_j^{inh} = p_{l,in,j} \cdot f \cdot E_{out}^{inh} + p_{l,out,j} \cdot E_{out}^{inh}, \quad (8)$$

where

E_{out}^{inh} Effective dose due to inhalation of radionuclide i in the radioactive cloud

f Filtering factor for a house

To prevent underestimation of doses in the calculation, the value of 1 was adopted for the filtering factor f.

E_{out}^{inh} is given as

$$E_{out}^{inh} = \sum_i \left(\frac{C_i \cdot A_{Cs137}(0)}{V_i} \right) \cdot B \cdot k_{inh,i}, \quad (9)$$

where

B Breathing rate for adults

$k_{inh,i}$ Effective dose coefficients for inhalation of radionuclides i

The value of 22.2 L d^{-1} was adopted as the breathing rate of adults from the recommendation of the International Commission on Radiological Protection (ICRP) Publication 71[15)]. The effective dose coefficients for inhalation were obtained from the same recommendation[15)].

(3) Input monitoring data of the surface activity density of ^{137}Cs

For each municipality of Fukushima Prefecture, **Table 5** lists the statistical values of the surface density of ^{137}Cs decay corrected to 0:00 on March 15, 2011 according to the data measured by MEXT[11)].

To determine the distribution form of the surface density of ^{137}Cs, normality tests were performed for the logarithmic values of the surface density for each municipality. The *p*-values of the tests for municipalities other than Fukushima City, Koriyama City, Nihonmatsu City, Tamura City, and Namie Town were higher than the significance level of 5%, so the null hypothesis was not rejected[7]. The normality tests for Fukushima City and Namie Town yielded *p*-values of 0.044 and 0.036, respectively. Because the values were close to 5%, these two municipalities were treated in the same manner as those without normality rejection. However, the *p*-values of the tests for the distributions for Koriyama City, Nihonmatsu City, and Tamura City were considerably lower than the significance level of 5%. Thus, the null hypothesis for these tests was rejected. Although the following assessments assume lognormality in the surface density distributions for municipalities including Koriyama City, Nihonmatsu City, and Tamura City, attention should be paid to the limitations mentioned above.

The geometric mean (GM) and geometric standard deviation (GSD) of the surface densities for each municipality of Fukushima Prefecture are listed in **Table 5**. Futaba Town, Okuma Town, and Namie Town are the most highly contaminated areas, and the values of the GM for the surface densities of ^{137}Cs are 1.53, 1.23, and 0.97 MBq m^{-2}, respectively. The next most highly contaminated municipalities are Iitate Village, Tomioka Town, and Katsurao Town, whose surface densities are 0.61, 0.60, and 0.26 MBq m^{-2}, respectively. The surface density levels of ^{137}Cs for the other municipalities of the Sousou area, i.e., Hirono Town, Kawauchi Village, Naraha Town, and Minami Soma City, are comparable to the levels for the municipalities in the Kenhoku and Kenchu areas.

The surface densities of ^{137}Cs in municipalities in the Kenhoku and Kenchu areas are around 0.1 MBq m^{-2} and 0.02 to 0.07 MBq m^{-2}, respectively. The surface density of ^{137}Cs for the Iwaki area, which comprises only Iwaki City, was the lowest among the values for the municipalities listed in the evacuation scenarios.

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[7] In other words, it concludes that the surface density data for these municipalities are from a lognormal-distributed population.

3. Results and discussion

(1) Estimated effective doses

a) Effective dose in the first year after the contamination event

Table 6 lists the 50^{th} and 95^{th} percentiles of the effective doses in the first year after the contamination, which were obtained from the probabilistic assessments. The following discussions are based on the 95^{th} percentile.

The effective doses received by the population groups of Namie Town and Iitate Village in the first year after the contamination were estimated to be in the 10–50 mSv dose band. Namie Town had two evacuation scenarios, 7 and 13. In evacuation scenario 7, the inhabitants were rapidly evacuated on March 16, 2011. On the other hand, the evacuation of Namie Town according to scenario 13 was implemented 7 days after evacuation scenario 7. The difference in the annual effective doses between the rapid evacuation (scenario 7) and the deliberate evacuation (scenario 13) is almost double for each population group. This result indicates that the doses received by the population living in the highly contaminated area were significantly influenced by the delay in evacuation in the early phase after the contamination.

However, there was no significant difference among the evacuation scenarios for inhabitants living in Iitate Village. The entire population of Iitate Village was evacuated 2–3 months after the accident onset. Thus, most of the inhabitants were already exposed to radiation before they were evacuated to Fukushima City. In our estimations, about 80% of the effective doses received by the inhabitants living in Iitate Village in the first year were delivered before the evacuation was implemented.

In addition, the effective doses received by outdoor workers had the potential to be above 10 mSv in the first year after the contamination in Minami Soma City, Katsurao Village and Fukushima City.

The annual effective doses received by the inhabitants evacuated according to scenarios 1–5, 8–12, 14, and 18 and to the inhabitants living in Koriyama City and Iwaki City were assessed to be in the 1–10 mSv dose band. The contributions to the annual effective dose from the doses received in the final evacuation facilities in the municipalities ranged 60%–75% for each scenario.

b) Effective lifetime doses

The lifetime doses received by the inhabitants of Fukushima City, Koriyama City, and Iwaki City are listed in **Table 7**. The values of the 95^{th} percentile of the effective doses to the three population groups are 13–32, 10–24, and 2.2–5.4 mSv in Fukushima City, Koriyama City and Iwaki City, respectively. For each city, 20%–30% of the lifetime effective dose was delivered during the first year.

(2) Contributions of different exposure pathways

Contributions of the doses from groundshine and inhalation to the annual effective dose are 85%–95% and 5%–15%, respectively. The contributions from cloudshine are much less than those from groundshine and inhalation. For several evacuation scenarios, the contribution of inhalation is larger than that mentioned above.

For evacuation scenarios 10, and the continuously living scenario of Iwaki City, the contributions of doses through inhalation range from 17% to 40%. Because the doses for these evacuation scenarios were calculated under the condition that radionuclides were deposited on dry property, the deposition velocities are less than those for average scenarios with a wet property. Thus, the dose contributions through inhalation are larger than those in average scenarios.

For evacuation scenarios 3 and 4, the inhabitants of Futaba Town were evacuated to Saitama Prefecture on March 19, 2011. The contamination level in Saitama Prefecture is considerably lower than that in Fukushima Prefecture. Therefore, the prolonged doses from groundshine after the evacuation to Saitama Prefecture are small. Consequently, the dose contributions through inhalation are larger than those in the other average scenarios.

The inhabitants of Namie Town were evacuated according to evacuation scenarios 7 and 13. These inhabitants received doses through internal exposure before evacuation from the highly contaminated area. Therefore, the doses through this pathway are larger than those through external exposure to groundshine in Nihonmatsu City after evacuation.

4. Conclusions

The present study assessed radiation doses in the first year after the contamination and over inhabitants' lifetimes caused by external exposure to groundshine and cloudshine as well as those due to internal exposures through inhalation. To assess the doses realistically and comprehensively, a probabilistic approach was employed using data that reflected realistic environmental trends and lifestyle habits in Fukushima

Prefecture.

The 95th percentile of the estimated annual effective dose for most of the population living in the municipalities listed in the evacuation scenarios was in the 1–10 mSv dose band. However, the doses received by some outdoor workers living in Minami Soma City, Katsurao City and Fukushima City could exceed 10 mSv. In addition, the inhabitants of Namie Town and Iitate Village were exposed to radiation doses in the 10–50 mSv dose band.

Contributions of the groundshine and inhalation doses to the annual effective dose are about 85%–95% and 5%–15%, respectively. However, the contributions from these pathways vary depending on deposition conditions, timing of evacuations, and differences in the contamination level of the ground surface.

It is noted that these assessments were performed on the basis of some important assumptions regarding the input data, assessment model, and the model's parameters. The doses must be assessed by iterative processes that reflect site-specific and realistic information derived from further investigations.

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Table 1 Evacuation scenarios for the population living in the evacuation area or the deliberate evacuation area based on the Fukushima Health Management Survey[3)]

Evacuation scenario No.	Municipality where the residence or evacuation facility is located and the length of stay during the period 11 Mar. '11 to 14 Mar. '12 [(1)]		
1	Tomioka Town ~06:00, 12 Mar. '11	Kawachi Village ~10:00, 16 Mar. '11	Koriyama City ~14 Mar. '12
2	Okuma Town ~13:00, 12 Mar. '11	Tamura City ~14 Mar. '12	—
3	Futaba Town ~08:00, 12 Mar. '11	Kawamata Town ~10:00, 19 Mar. '11	Saitama Prefecture ~14 Mar. '12
4	Futaba Town ~16:00, 12 Mar. '11	Kawamata Town ~10:00, 19 Mar. '11	Saitama Prefecture ~14 Mar. '12
5	Naraha Town ~13:00, 12 Mar. '11	Iwaki City ~10:00, 31 Mar. '11	Tamura City ~14 Mar. '12
6	Naraha Town ~13:00, 12 Mar. '11	Iwaki City ~10:00, 16 Mar. '11	Aizu Misato Town ~14 Mar. '12
7	Namie Town ~10:00, 15 Mar. '11	Namie Town ~10:00, 16 Mar. '11	Nihonmatsu City ~14 Mar. '12
8	Tamura City ~08:00, 12 Mar. '11	Tamura City ~10:00, 31 Mar. '11	Koriyama City ~14 Mar. '12
9	Minami Soma City ~10:00, 15 Mar. '11	Date City ~10:00, 31 Mar. '11	Fukushima City ~14 Mar. '12
10	Hirono Town ~08:00, 12 Mar. '11	Ono Town ~14 Mar. 2012	—
11	Kawachi Village ~10:00, 13 Mar. '11	Kawachi Village ~10:00, 16 Mar. '11	Koriyama City ~14 Mar. '12
12	Katsurao Village ~10:00, 14 Mar. '11	Fukushima City ~14 Mar. '12	—
13	Namie Town ~10:00, 23 Mar. '11	Nihonmatsu City ~14 Mar. '12	—
14	Katsurao Village ~10:00, 21 Mar. '11	Fukushima City ~14 Mar. '12	—
15	Iitate Village ~10:00, 29 May '11	Fukushima City ~14 Mar. '12	—
16	Iitate Village ~10:00, 21 Jun. '11	Fukushima City ~14 Mar. '12	—
17	Minami Soma City ~10:00, 20 May '11	Minami soma City ~14 Mar. '12	—
18	Kawamata Town ~10:00, 1 Jun. '11	Kawamata Town ~14 Mar. '12	—

(1) The dose assessments were performed with the assumption that the inhabitants stayed in the same municipality after movement to the final evacuation facility.

Table 2 Parameters for location factors of cesium for an urban environment[6)]

Type of Location	$a_{l,1}$	$a_{l,2}$	T_l (years)
Virgin land	0.32	0.68	1.4
Dirt surface	0.50	0.25	2.2
Asphalt	0.56	0.12	0.9

Table 3 Statistical values to determine the probabilistic distribution functions of $t_{l,in(\text{or } out),j}$ for each population group

Population group[(1)]	Distribution form	Mean	Deviation
Indoor worker	Log-normal	0.57[(2)]	3.28[(4)]
Outdoor worker	Normal	6.97[(3)]	2.90[(5)]
Pensioner	Log-normal	1.27[(2)]	3.37[(4)]

(1) Indoor worker means Fukushima City officers. Outdoor worker includes construction workers and farmers.

(2) GM, (3) AM, (4) GSD, (5) SD

Table 4 Composition of radionuclides deposited on March 15, 2011[2)]

Radionuclides	Deposited activity normalized by ^{137}Cs
^{131}I	11.7
^{132}I	—[(1)]
^{132}Te	8.0
^{134}Cs	0.94
^{136}Cs	0.2
^{137}Cs	1.0
^{140}Ba	0.1
^{140}La	—[(1)]
^{110m}Ag	0.01
^{129m}Te	1.5

(1) The activity of ^{132}I and ^{140}La were derived from that of the parent nuclide, i.e., ^{132}Te and ^{140}Ba, assuming radioactive equilibriums.

Table 5 Surface density of ^{137}Cs for each municipality of Fukushima Prefecture

Area	Municipality	Sample size	GM	GSD
Kenhoku area	Date City	60	1.29E+05	1.94E+00
	Kawamata Town	38	1.40E+05	1.87E+00
	Nihonmatsu City	82	1.20E+05	2.00E+00
	Fukushima City	94	1.25E+05	2.13E+00
Kenchu area	Koriyama City	118	6.76E+04	2.71E+00
	Ono Town	31	2.16E+04	1.48E+00
	Tamura City	109	3.78E+04	2.81E+00
Aizu area	Aizu Misato Town	2	1.22E+04	1.34E+00
Sousou area	Katsurao Town	18	2.56E+05	1.94E+00
	Hirono Town	14	6.79E+04	1.77E+00
	Kawauchi Village	37	1.01E+05	2.42E+00
	Futaba Town	9	1.53E+06	3.67E+00
	Okuma Town	14	1.23E+06	3.90E+00
	Naraha Town	16	9.18E+04	2.61E+00
	Minami Soma City	78	1.06E+05	2.81E+00
	Iitate Village	53	6.08E+05	1.77E+00
	Tomioka Town	16	5.98E+05	2.90E+00
	Namie Town	38	9.66E+05	4.02E+00
Iawaki area	Iwaki City	266	2.15E+04	2.14E+00

Table 7 Effective lifetime doses (60 years) (mSv)

	Pensioner 50%–95%	Indoor Worker 50%–95%	Outdoor Worker 50%–95%
Fukushima City	4.2–15	3.8–13	8.4–32
Koriyama City	2.3–11	2.1–10	4.5–24
Iwaki City	0.92–2.5	0.87–2.2	1.6–5.4

Table 6 Effective doses in the first year after the contamination (mSv) (1/2)

	Evacuation Scenario No.		Pensioner	Indoor Worker	Outdoor Worker	WHO[2] (1)
Tomioka Town	1	50%–95%	1.1–4.1	1.0–3.9	1.7–7.3	—
		Groundshine	89%	88%	93%	
		Cloudshine	1%	1%	1%	
		Inhalation	10%	11%	6%	
Okuma Town	2	50%–95%	0.62–2.9	0.58–2.5	0.91–4.3	—
		Groundshine	86%	85%	91%	
		Cloudshine	1%	1%	1%	
		Inhalation	13%	14%	8%	
Futaba Town	3, 4	50%–95%	0.39–1.1	0.37–0.99	0.50–1.4	—
		Groundshine	60%	57%	69%	
		Cloudshine	3%	3%	2%	
		Inhalation	37%	40%	29%	
Hirono Town	10	50%–95%	0.47–0.72	0.44–0.64	0.66–1.1	—
		Groundshine	64%	62%	74%	
		Cloudshine	3%	3%	2%	
		Inhalation	33%	35%	24%	
Naraha Town	5	50%– 95%	0.60–2.1	0.56–1.9	0.89–3.6	1–10
		Groundshine	84%	83%	90%	
		Cloudshine	1%	1%	1%	
		Inhalation	15%	16%	9%	
	6	50%–95%	0.30–0.48	0.28–0.45	0.41–0.64	
		Groundshine	58%	55%	68%	
		Cloudshine	3%	3%	2%	
		Inhalation	39%	42%	30%	
Namie Town	7	50%–95%	3.7–16	3.4–15	5.2–20	10–50
		Groundshine	56%	53%	67%	
		Cloudshine	3%	3%	2%	
		Inhalation	41%	44%	31%	
	13	50%–95%	5.2–34	4.9–31	7.6–48	
		Groundshine	75%	73%	82%	
		Cloudshine	2%	2%	1%	
		Inhalation	23%	25%	17%	
Minami Soma City	9	50%–95%	2.0–5.0	1.8–4.5	3.0–8.5	1–10
		Groundshine	92%	92%	95%	
		Cloudshine	1%	1%	0%	
		Inhalation	7%	7%	5%	
	17	50%–95%	1.6–8.1	1.4–7.3	2.4–13	
		Groundshine	82%	91%	95%	
		Cloudshine	0%	0%	0%	
		Inhalation	8%	9%	5%	
Iitate Village	15	50%–95%	5.6–13	5.2–12	8.3–20	10–50
		Groundshine	88%	86%	91%	
		Cloudshine	1%	1%	1%	
		Inhalation	11%	13%	8%	
	16	50%–95%	5.9–14	5.5–13	8.8–22	
		Groundshine	88%	87%	92%	
		Cloudshine	1%	1%	1%	
		Inhalation	11%	12%	7%	

* Contributions of exposure pathways were calculated using the arithmetic mean of the distributions of each pathway.

(1) It is noted that the estimated values by WHO include contributions of internal exposures from ingestion of radionuclides in food and water.

Table 6 Effective doses in the first year after the contamination (mSv) (2/2)

	Evacuation scenario No.		Pensioner	Indoor Worker	Outdoor Worker	WHO[2] (1)
Tamura City	8	50%–95%	1.0–3.6	0.9–3.3	1.5–6.2	—
		Groundshine	90%	89%	94%	
		Cloudshine	1%	1%	0%	
		Inhalation	9%	10%	6%	
Kawamata Town	18	50%–95%	2.0–5.6	1.8–5.0	3.1–8.6	—
		Groundshine	92%	92%	95%	
		Cloudshine	1%	1%	0%	
		Inhalation	7%	7%	5%	
Kawachi Village	11	50%–95%	1.1–4.5	1.1–3.9	1.7–7.6	—
		Groundshine	89%	88%	93%	
		Cloudshine	1%	1%	1%	
		Inhalation	10%	11%	6%	
Katsurao Village	12	50%–95%	1.8–6.2	1.6–5.5	2.8–10	1–10
		Groundshine	92%	91%	95%	
		Cloudshine	1%	1%	0%	
		Inhalation	7%	8%	5%	
	14	50%–95%	2.4–6.0	2.2–5.3	3.7–9.8	
		Groundshine	88%	86%	92%	
		Cloudshine	1%	1%	1%	
		Inhalation	12%	13%	7%	
Fukushima City	—(2)	50%–95%	1.8–6.3	1.6–5.5	2.8–10	—
		Groundshine	91%	95%	95%	
		Cloudshine	1%	0%	0%	
		Inhalation	8%	5%	5%	
Koriyama City	—(2)	50%–95%	0.96–4.8	0.88–4.3	1.5–7.8	—
		Groundshine	90%	89%	94%	
		Cloudshine	1%	1%	1%	
		Inhalation	9%	10%	5%	
Iwaki City	—(2)	50%–95%	0.46–1.1	0.44–0.93	0.66–1.7	1–10
		Groundshine	74%	72%	82%	
		Cloudshine	2%	2%	1%	
		Inhalation	24%	26%	17%	

* Contributions of exposure pathways were calculated using the arithmetic mean of the distributions of each pathway

(1) It is noted that the estimated values by WHO include contributions of internal exposures from ingestion of radionuclides in food and water.

(2) Assessments of doses were performed with the assumption that the inhabitants had lived continuously in these cities during the first year after the contamination occurred.