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Original Article

Estimation of long-term effective doses for residents in the regions of Japan following Fukushima accident

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ABSTRACT

A large amount of radioactive material was released from the Fukushima Daiichi Nuclear Power Plant (FDNPP) in 2011 and dispersed into the environment. Though seven years have passed since the Fukushima Daiichi Nuclear Power Plant accident, some parts of Japan are still under the influence of radionuclide contamination, especially Fukushima Prefecture and prefectures neighboring Fukushima Prefecture. The long-term effective doses and the contributions of each exposure pathway (5 exposure pathways) and radionuclide (^{131}I, ^{134}Cs, and ^{137}Cs) were evaluated for people living in the regions of Fukushima and neighboring prefectures in Japan using a developed dose assessment code system with Japanese specific input data. The results estimated in this study were compared with data from previously published reports. Groundshine and ingestion were predicted to contribute most significantly to the total long-term dose for all regions. The contributions of each exposure pathway and radionuclide show different patterns for certain regions of Japan.

1. Introduction

Following the Fukushima Daiichi Nuclear Power Plant (FDNPP) accident, a significant amount of radionuclides was released and dispersed into the environment. After the FDNPP accident, an extensive area of Japan was contaminated by radioactive material released from the FDNPP, especially Fukushima Prefecture and prefectures neighboring Fukushima Prefecture, and resulting public exposure through various pathways. Thirty two years have passed since the Chernobyl accident, but the surrounding area is still suffering from radioactive contamination. Seven years have passed since the FDNPP accident, but Japan will be affected by the contaminated radioactive environment over the next several decades. It is important to estimate radiological effects on people living in contaminated areas for the long-term phase and prepare countermeasures or decontamination to minimize the impacts of the accident.

A dose assessment system has been recently developed to evaluate the radiological doses to the public following nuclear accidents. The dose assessment code system considers five exposure pathways, as follows: external exposure to radionuclide in air (cloudshine), external exposure from deposited radionuclide on the ground (groundshine), internal exposure from inhalation of radionuclide in air (inhalation), internal exposure from inhalation of resuspended radionuclide (resuspension inhalation), and internal exposure from ingestion of contaminated agricultural food.

In this research, following the FDNPP accident, the long-term effective doses were calculated for people living in the regions of Fukushima Prefecture and neighboring prefectures using the developed dose assessment code system with Japanese specific input data. The results estimated using the developed dose assessment code system were compared with data from previously published reports.

2. Materials and methods

2.1. Dose assessment code system

Dose assessment was performed using our code system. The model calculates the effective and equivalent doses to male adults for short-, intermediate-, and long-term periods (up to 7 days, 6 months, and 50 years from the accident date, respectively) from radionuclides accidentally released into the atmosphere. Radionuclide concentrations in the air (Bq/m^3) and radionuclide deposited on the ground (Bq/m^2), on a daily basis within 30 days of accident in the regions are applied as source-term data. The Korean

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environment, lifestyle, and dietary habits were reflected in the developed dose assessment system. Five exposure pathways are considered: cloudshine, groundshine, inhalation, resuspension inhalation, and ingestion. The code takes into account the parent and first daughter radionuclides. More details regarding the dose assessment code system are given in Kim et al. (2018) [1].

Doses from ingestion were estimated using a food chain model, named LARIAS (Land and Aquatic Radionuclide transport and Ingestion dose Assessment System), which is under development for calculating radionuclide transfer and ingestion doses through the terrestrial and aquatic food chain in Korea following the nuclear accident. The current version of LARIAS only has the terrestrial food chain model, and the aquatic food chain model is under development. The terrestrial food chain model of LARIAS estimates radionuclide transfer through the terrestrial food chain and resulting ingestion doses under the Korean agricultural environment following accidental releases. The model considers 7 types of agricultural products and 5 types of livestock. We already performed a comparative study of LARIAS and the FARMLAND (Food and Activity from Radionuclide Movement on Land) model, which is a terrestrial food chain model developed by the National Radiological Protection Board (NRPB). The simulation results of LARIAS showed comparable values to those of the FARMLAND model. Details of LARIAS are given in Kim et al. (2018) [2].

For calculation verification of the model, we performed a time convergence study on LARIAS. Radioactivity concentration was estimated to converge to zero in each compartment as time went to infinity. We also compared the simulation results of our code (except for the results of LARIAS) with those calculated by Microsoft Excel 2013 using the same equations, assumptions, and input data to check that the code conducts the calculations correctly.

There was no difficulty in applying our dose assessment code system in Japan, because Japan has a relatively similar environment to those of Korea. Also, dose assessment was performed as much as possible reflecting Japanese specific data.

2.2. Input data and assumptions for dose assessment

It was assumed that the accident was occurred on 11 March 2011 and ^{131}I, ^{134}Cs, and ^{137}Cs were released into the atmosphere from the FDNPP. The assessment was performed for 3 cities (or villages) of Fukushima Prefecture, excluding the evacuated regions, and 8 cities (or villages, towns) of prefectures neighboring Fukushima Prefecture (prefectures of Gunma, Miyagi, Tochigi, and Ibaraki) in Japan: Fukushima City, Soma City, and Hinoemata Village in Fukushima Prefecture, Kawaba Village and Katashina Village in Gunma Prefecture, Hitachi City and Hitachiomiya City in Ibaraki Prefecture, Marumori Town and Kawasaki Town in Miyagi Prefecture, and Nasu Town and Utsunomiya City in Tochigi Prefecture (Fig. 1 [3]). The cities with the highest and lowest ^{137}Cs deposition concentrations in each prefecture were selected for assessment with reference to attachment C-14 of the 2013 UNSCEAR (United Nations Scientific Committee on the Effects of Atomic Radiation) report [4]. The evacuated regions are those from which people were evacuated within months after the FDNPP accident according to evacuation scenarios. The regions considered in the assessment referred to the classification of geographic areas from the 2013 UNSCEAR report [4].

Japanese specific habits and environmental parameters, which are provided in attachment C-12 and C-13 of the 2013 UNSCEAR report [4], were used in the assessment. In case of ingestion dose, estimation was entirely based on our previous research [2] and some additional calculations were made with 2 different assumptions of food consumption, as follows: Assumption 1: People consumed 100% of their food from their local prefectures. People

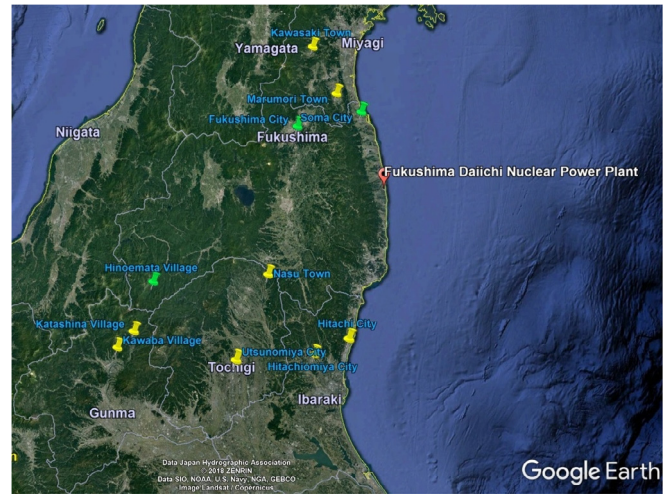

Fig. 1. Locations of 3 cities in Fukushima Prefecture and 8 cities in prefectures neighboring (prefectures of Gunma, Miyagi, Tochigi, and Ibaraki) Fukushima Prefecture of Japan selected for dose assessment following the Fukushima Daiichi Nuclear Power Plant (FDNPP) accident (Google Earth, 2018 [3]).

living in Fukushima City, Soma City, and Hinoemata Village were assumed to consume food produced in Fukushima Prefecture, excluding the evacuated regions. People living in the other 8 cities were assumed to consmue food produced in the 4 neighboring and 2 prefectures near Fukushima Prefecture (prefectures of Gunma, Miyagi, Tochigi, Ibaraki, Chiba, and Iwate). Assumption 2: For the first year following the accident, people consumed 100% of their food from their local prefectures, with food restrictions. For the subsequent years, people consumed 25% of their food from their local prefectures and 75% from the rest of Japan (all remaining prefectures of Japan), with food restrictions. According to the 2013 UNSCEAR report [4], from March 2011 to the end of March 2012, food restriction was introduced in Japan to limit radiation exposure. Activity concentrations of restriction level are as follows. Iodine: 300 Bq/kg for milk, 2000 Bq/kg for other foods; Cesium: 200 Bq/kg for milk, 500 Bq/kg for other foods. After April 2012, lower values were introduced for cesium: 50 Bq/kg for milk, 100 Bq/kg for other foods.

External dose coefficients were obtained from Federal Guidance Report No. 12 (FGR 12) [5]. Inhalation and ingestion dose coefficients were obtained from International Commission on Radiological Protection (ICRP) Publication 72 [6].

2.3. Radionuclide concentration data

Time-integrated concentrations (Bq d/m^3) of radionuclides in air, which were simulated using the NOAA (National Oceanic and Atmospheric Administration)-GDAS (Global Data Assimilation System) model for the period from 12 March to 1 April 2011, for 11 cities, were taken from attachment C-9 of the 2013 UNSCEAR report [4]. Average deposition densities (Bq/m^2) of ^{137}Cs for cities were taken from attachment C-14 of the 2013 UNSCEAR report [4]. Deposition concentraions of ^{131}I and ^{134}Cs were calculated using radionuclide ratios to ^{137}Cs; these values were 1.0 and 11.5, respectively. Radionuclide ratios were taken from attachment C-12 of the 2013 UNSCEAR report [4].

2.4. Published data from previous reports

We compared our results with previously published data from the 2013 UNSCEAR report [4] and the 2012 WHO (World Health

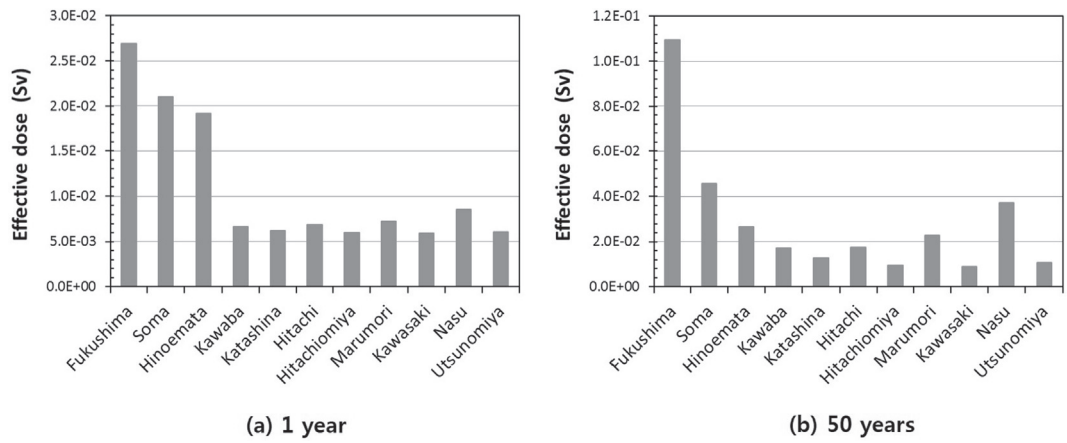

Fig. 2. Effective doses to people living in 11 cities of Japan over (a) 1 year and (b) 50 years following the Fukushima Daiichi Nuclear Power Plant (FDNPP) accident. It was assumed that people consumed food produced 100% locally (with assumption 1).

Organization) report [7]. UNSCEAR has been working on monitoring and evaluating new information that has appeared after releasing the 2013 UNSCEAR report [4]. Over 300 publications have been reviewed by expert groups to idendify new scientific developments and 3 white papers were published in 2015, 2016, and 2017 [8–10]. According to the white papers [8–10], the main assumptions and findings of the 2013 UNSCEAR report [4] remained broadly valid and were not significantly affected by subsequent published information. Therefore, the results evaluated in this study were mainly compared with data from the 2013 UNSCEAR report [4].

3. Results and discussion

3.1. Long-term effective doses to residents

The effective doses from five exposure pathways were calculated for people living in 11 cities of Japan over 1 and 50 years following the FDNPP accident. As already mentioned, the assessment was performed for 2 cases with 2 different assumptions of food consumption. Figs. 2 and 3 show the effective doses predicted for 1 and 50 years with assumptions 1 and 2. No countermeasures or decontamination was taken into account except for food restrictions in assumption 2.

As shown in Fig. 2, Fukushima City shows the highest effective dose among the 11 cities. By making assumption 2 (Fig. 3), the total effective doses were estimated to be greatly decreased for all cities, compared to those of assumption 1 (Fig. 2).

3.2. Contributions of each exposure pathway and radionuclide to effective dose (except ingestion dose)

Tables 1 and 2 show the total effective doses except ingestion doses and contributions of each exposure pathway to residents in 11 cities for 1 year and 50 years following the accident. In the case of the effective doses (except ingestion dose) for 50 years, the contribution by groundshine accounted for more than 97%, followed by inhalation, which is very low, less than 3% in all cities. There were no significant differences in the contributions of each exposure pathway to total dose between cities. In case of the effective doses (except ingestion dose) for 1 year, groundshine was estimated to contribute more than 94% in most cities except Hitachi City, Hitachiomiya City, and Kawasaki Town. Unlike other cities, the above 3 cities accounted for more than 10% of the total dose by inhalation, especially the value of approximately 23% in Hitachiomiya City. Fukushima City, Nasu Town, and Soma City showed the highest values of long-term effective dose (except ingestion dose) among the 11 cities.

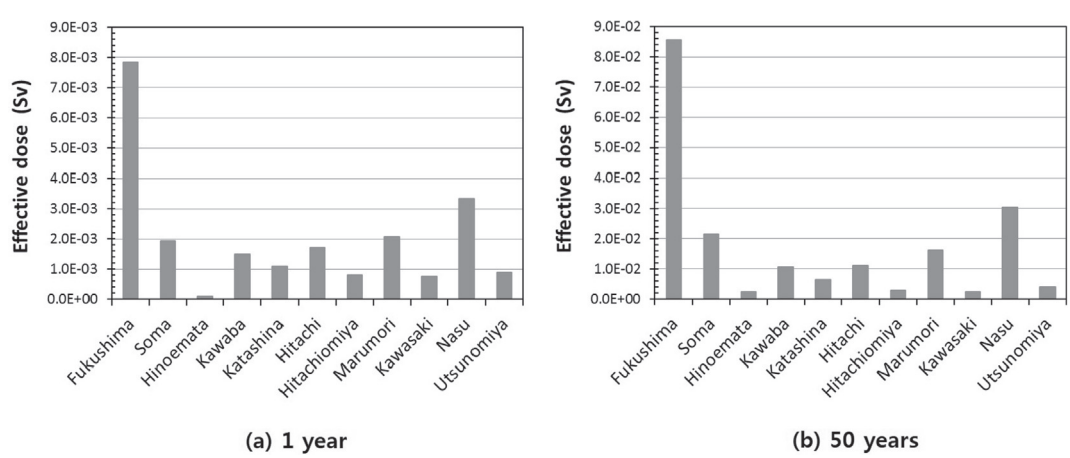

Fig. 3. Effective doses to people living in 11 cities of Japan over (a) 1 year and (b) 50 years following the Fukushima Daiichi Nuclear Power Plant (FDNPP) accident. It was assumed that people consumed food produced 100% locally for the first year following the accident and consumed 25% of their food from local prefectures and 75% from the rest of Japan for subsequent years, with food restrictions (with assumption 2).

Table 1
Contributions of each exposure pathway to the effective doses (except ingestion dose) to people living in 11 cities of Japan over 1 year following the Fukushima Daiichi Nuclear Power Plant (FDNPP) accident.

	Contributions (%)[a] of each exposure pathway to toal dose (except ingestion dose)				Total dose (except ingestion dose) (Sv)
	Cloudshine	Groundshine	Inhalation	Resuspension inhalation	
Fukushima City	0.00	99.41	0.46	0.13	7.83E-03
Soma City	0.02	96.68	3.18	0.12	1.91E-03
Hinoemata Village	0.00	99.32	0.55	0.13	8.28E-05
Kawaba Village	0.00	99.67	0.20	0.13	8.83E-04
Katashina Village	0.00	99.53	0.34	0.13	4.79E-04
Hitachi City	0.12	82.19	17.58	0.10	1.09E-03
Hitachiomiya City	0.15	76.41	23.34	0.10	1.95E-04
Marumori Town	0.03	96.13	3.72	0.12	1.45E-03
Kawasaki Town	0.08	87.50	12.31	0.11	1.37E-04
Nasu Town	0.00	99.54	0.33	0.13	2.72E-03
Utsunomiya City	0.03	94.60	5.25	0.12	2.81E-04

[a] Rounded off to the second decimal place.

Table 2
Contributions of each exposure pathway to the effective doses (except ingestion dose) to people living in 11 cities of Japan over 50 years following the Fukushima Daiichi Nuclear Power Plant (FDNPP) accident.

	Contributions (%)[a] of each exposure pathway to toal dose (except ingestion dose)				Total dose (except ingestion dose) (Sv)
	Cloudshine	Groundshine	Inhalation	Resuspension inhalation	
Fukushima City	0.00	99.94	0.04	0.01	8.39E-02
Soma City	0.00	99.68	0.30	0.01	2.00E-02
Hinoemata Village	0.00	99.94	0.05	0.01	8.86E-04
Kawaba Village	0.00	99.97	0.02	0.01	9.48E-03
Katashina Village	0.00	99.96	0.03	0.01	5.14E-03
Hitachi City	0.01	98.03	1.95	0.01	9.85E-03
Hitachiomiya City	0.02	97.21	2.76	0.01	1.65E-03
Marumori Town	0.00	99.63	0.36	0.01	1.51E-02
Kawasaki Town	0.01	98.69	1.29	0.01	1.31E-03
Nasu Town	0.00	99.96	0.03	0.01	2.92E-02
Utsunomiya City	0.00	99.47	0.51	0.01	2.88E-03

[a] Rounded off to the second decimal place.

Table 3 shows the contributions of each radionuclide to the effective doses (except ingestion dose) to people living in 11 cities for 1 and 50 years following the accident. The contributions of each radionuclide to doses for 1 and 50 years show significantly different tendencies. This variation seems to be largely affected by the physical half-lives of the radionuclides, which are 8.04 days, 2.06, and 30.03 years for ^{131}I, ^{134}Cs, and ^{137}Cs, respectively. The contributions of each radionuclide to doses for 50 years were estimated to be about 20–22% for ^{134}Cs, about 76–79% for ^{137}Cs, and less than about 3% for ^{131}I, with no significant differences among cities. However, in the case of the 1-year exposure dose, the contributions of each radionuclide show relatively large differences among cities. In particular, ^{131}I contributed significantly more in Hitachi City, Hitachiomiya City and Kwasaki Town to the total dose (except ingestion dose) of each city compared to the other cities. The contribution of ^{131}I to long-term dose was mostly due to exposure within a few months of the accident because of its short physical half-life. Due to the large difference in the physical half-lives between radionuclides, it seems that the biological half-life does not significantly affect the results, but it should be kept in mind that the biological half-life is also an important factor in dose assessment, especially in evaluating internal exposure doses.

Table 3
Contributions of each radionuclide to the effective doses (except ingestion dose) to people living in 11 cities of Japan over 1 and 50 years following the Fukushima Daiichi Nuclear Power Plant (FDNPP) accident.

	Contributions (%)[a] of each radionuclide to toal dose (except ingestion dose)					
	1 year			50 years		
	^{131}I	^{134}Cs	^{137}Cs	^{131}I	^{134}Cs	^{137}Cs
Fukushima City	7.31	64.73	27.96	0.68	21.16	78.16
Soma City	9.45	63.19	27.37	0.90	21.13	77.97
Hinoemata Village	7.39	64.67	27.94	0.69	21.15	78.16
Kawaba Village	7.08	64.88	28.03	0.66	21.16	78.18
Katashina Village	7.19	64.81	28.00	0.67	21.15	78.18
Hitachi City	20.99	54.93	24.08	2.32	20.91	76.77
Hitachiomiya City	26.07	51.36	22.57	3.08	20.77	76.16
Marumori Town	9.91	62.86	27.23	0.95	21.12	77.93
Kawasaki Town	16.69	58.00	25.31	1.75	21.00	77.26
Nasu Town	7.21	64.79	28.00	0.67	21.16	78.17
Utsunomiya City	11.24	61.92	26.84	1.10	21.08	77.82

[a] Rounded off to the second decimal place.

Taking all of Table 1 ~ 3 into consideration, it is expected that the influence of internal exposure from inhalation of ^{131}I is relatively large in Hitachi City, Hitachiomiya City, and Kwasaki Town compared to other cities. Figure C–IV in the 2013 UNSCEAR report [4] shows the pattern of time-integrated concentration of ^{131}I in air, which is the result of the NOAA-GDAS atmospheric modelling analyses. According to the pattern shown, among all prefectures except Fukushima Prefecture, time-integrated concentration of ^{131}I shows relatively high levels in the regions of Ibaraki Prefecture, including Hitachi City and Hitachiomiya City.

3.3. Estimated effective doses from ingestion of contaminated food

Ingestion doses were calculated with two different assumptions of food consumption. The conservative assumption was applied for the first assumption, in which people consumed 100% locally

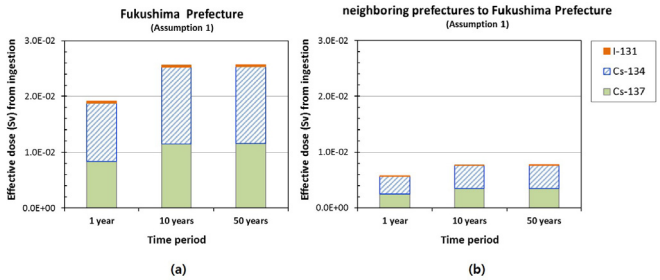

Fig. 4. Ingestion doses from ^{131}I, ^{134}Cs, and ^{137}Cs for residents in cities of (a) Fukushima Prefecture (excluding the evacuated regions) and (b) prefectures neighboring Fukushima Prefecture. Calculation was performed with assumption 1.

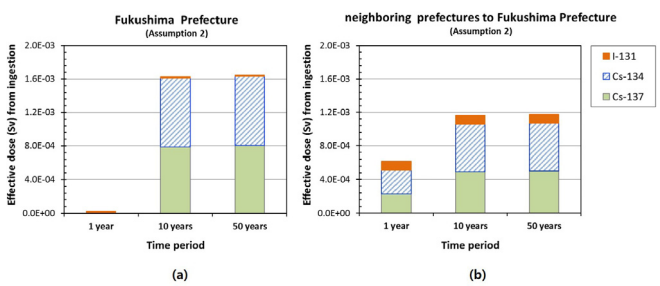

Fig. 5. Ingestion doses from ^{131}I, ^{134}Cs, and ^{137}Cs for residents in cities of (a) Fukushima Prefecture (excluding the evacuated regions) and (b) prefectures neighboring Fukushima Prefecture. Calculation was performed with assumption 2.

produced food in their local prefecture without food restriction. The second assumption was based on the assumption used in the FARMAND model simulation, which is represented in the 2013 UNSCEAR report [4], to estimate ingestion dose from consuming agricultural products and livestock to people living in the regions of Japan after the FDNPP accident. The second assumption was that people consumed 100% locally produced food in their local prefectures with food restriction for the first year following the accident. People consumed 25% of food from the local prefecture and 75% from the rest of Japan with food restrictions for the subsequent years. As already mentioned in the Material and Methods section, residents in Fukushima City, Soma City, and Hinoemata Village were assumed to consume food produced in Fukushima Prefecture, excluding the evacuated regions. People living in the other 8 cities were assumed to consume food produced in the 4 prefectures neighboring and 2 prefectures near Fukushima Prefecture, which are the prefectures of Gunma, Miyagi, Tochigi, Ibaraki, Chiba, and Iwate.

Figs. 4 and 5 show ingestion doses from ^{131}I, ^{134}Cs, and ^{137}Cs for people living in cities of Fukushima Prefecture, excluding the evacuated regions and prefectures neighboring Fukushima Prefecture, over 1, 10, and 50 years following the accident with assumptions 1 and 2, respectively. According to the results represented in Fig. 4, the effective doses from ingestion were estimated to be about 3–4 times higher for residents in Fukushima Prefecture than in neighboring prefectures with assumption 1.

In the case of the results shown in Fig. 5, ingestion dose in cities of Fukushima Prefecture (excluding the evacuated regions) shows a very low value for 1 year, about 2.25E-5 Sv. This is because a large portion of food stuff was predicted to be contaminated with radionuclide above the level of food restriction.

3.4. Comparing results with previously published data

Table 4 shows the estimated effective doses from 5 exposure pathways to people living in 11 cities over 1 year after the accident with assumption 2. Although the results of the total effective doses, shown in Table 4, were already presented in Fig. 3 (a), those values were presented again to allow a comparison of the results of our dose assessment code system with those obtained from the 2013 UNSCEAR report [4]. Table 5 shows the effective doses to adults in the first year after the FDNPP accident for 11 cities; these values were taken from attachment C-14 of the 2013 UNSCEAR report [4]. Although there are some differences in the results shown in Tables 4 and 5, the contributions of each exposure pathway to the total dose and the total dose of each city calculated using our dose assessment model showed values comparable with those of data from the 2013 UNSCEAR report [4].

The 2012 WHO report [7] provides data on the estimated effective doses to the public living in the different regions of Japan in the first year following the FDNPP accident. These values are as follows: doses in most affected regions of Fukushima Prefecture were within a range of 1.0E-2 to 5.0E-2 Sv. Doses in the rest of Fukushima Prefecture, which are less affected areas, were within a range of 1.0E-3 to 1.0E-2 Sv. Doses for prefectures neighboring Fukushima Prefecture, which are Chiba, Gunma, Ibaraki, Miyagi, and Tochigi, were within a range of 1.0E-4 to 1.0E-2 Sv.

According to the region classification of the 2012 WHO report [7], Fukushima City and Soma City are in most affected regions of Fukushima Prefecture and Hinoemata Village is included in a less affected area of Fukushima Prefecture. The other 8 cities are included in neighboring prefectures. As shown in Table 4, the calculated doses of our code system for cities of Fukushima Prefecture were about 1 order of magnitude lower than the results from the 2012 WHO report [7]. The doses calculated for the other 8 cities showed results comparable with those of the 2012 WHO

Table 4
Effective doses from each exposure pathway to people living in 11 cities of Japan over 1 year following the Fukushima Daiichi Nuclear Power Plant (FDNPP) accident, with the assumption that people consumed 100% of their food from local prefectures for the first year following the accident and consumed 25% of their food from the local prefecture and 75% from the rest of Japan for subsequent years, with food restrictions (with assumption 2).

City	Effective dose (Sv)					
	Cloudshine	Groundshine	Inhalation	Resuspension inhalation	Food ingestion	Total Dose
Fukushima City	2.22E-07	7.78E-03	3.59E-05	9.84E-06	2.25E-05	7.85E-03
Soma City	4.20E-07	1.85E-03	6.07E-05	2.34E-06	2.25E-05	1.93E-03
Hinoemata Village	3.00E-09	8.22E-05	4.56E-07	1.04E-07	2.25E-05	1.05E-04
Kawaba Village	1.29E-08	8.80E-04	1.76E-06	1.11E-06	6.16E-04	1.50E-03
Katashina Village	1.16E-08	4.77E-04	1.64E-06	6.03E-07	6.16E-04	1.10E-03
Hitachi City	1.30E-06	8.97E-04	1.92E-04	1.13E-06	6.16E-04	1.71E-03
Hitachiomiya City	2.96E-07	1.49E-04	4.55E-05	1.88E-07	6.16E-04	8.11E-04
Marumori Town	3.67E-07	1.39E-03	5.40E-05	1.76E-06	6.16E-04	2.07E-03
Kawasaki Town	1.16E-07	1.20E-04	1.69E-05	1.52E-07	6.16E-04	7.53E-04
Nasu Town	5.99E-08	2.71E-03	8.99E-06	3.43E-06	6.16E-04	3.34E-03
Utsunomiya City	9.60E-08	2.66E-04	1.47E-05	3.36E-07	6.16E-04	8.97E-04

Table 5
Effective doses to adults in the first year after the Fukushima Daiichi Nuclear Power Plant (FDNPP) accident for 11 cities. Data taken from attachment C-14 of the 2013 UNSCEAR report [4].

City	Effective dose (Sv)					
	Cloudshine	Groundshine	Inhalation	Resuspension inhalation	Food ingestion	Total Dose
Fukushima City	0.00	3.02E-3	3.00E-4	–	9.40E-4	4.26E-3
Soma City	0.00	6.90E-4	4.00E-5	–	9.40E-4	1.67E-3
Hinoemata Village	0.00	3.00E-5	0.00	–	9.40E-4	9.70E-4
Kawaba Village	0.00	3.60E-4	4.00E-5	–	2.10E-4	6.00E-4
Katashina Village	0.00	2.00E-4	2.00E-5	–	2.10E-4	4.20E-4
Hitachi City	0.00	3.50E-4	4.00E-5	–	2.10E-4	6.00E-4
Hitachiomiya City	0.00	6.00E-5	1.00E-5	–	2.10E-4	2.70E-4
Marumori Town	0.00	5.50E-4	6.00E-5	–	2.10E-4	8.10E-4
Kawasaki Town	0.00	5.00E-5	0.00	–	2.10E-4	2.60E-4
Nasu Town	0.00	1.07E-3	1.10E-4	–	2.10E-4	1.39E-3
Utsunomiya City	0.00	1.10E-4	1.00E-5	–	2.10E-4	3.20E-4

report [7]. When comparing results, it should be noted that there are differences in the detailed assumptions applied in the dose assessments.

4. Conclusions

Despite the fact that seven years have passed since the FDNPP accident, some regions of Japan are still contaminated with radioactive materials. Japan will be affected by the contaminated radioactive environment over the next several decades. It is important to perform the realistic assessment of radiological effects on people living in contaminated areas for the long-term phase and take appropriate actions of countermeasures or decontamination to effectively reduce the impacts of the accident. The code calculated the long-term effective doses from 5 exposure pathways in Fukushima Prefecture and neighboring prefectures, which are relatively highly contaminated regions of Japan following the FDNPP accident. External exposure to contaminated soil and ingestion of contaminated food were estimated to contribute most significantly to the total effective dose in the long-term period for all regions. The contributions of each exposure pathway and radionuclide were predicted to show different patterns for certain regions of Japan.

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