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## Original Research

### Internal radioactivity of temporary residents in Fukushima within one year after the radiological accident

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**Key words:** radioactivity, radiological accident

**Abstract**

**Aim:** In an attempt to estimate the chronological changes of health risk in Fukushima, the internal radiation doses of temporary residents in Fukushima were analyzed.

**Method:** The internal radioactivity of 372 persons who were dispatched to the Fukushima prefecture at any time from April 2011 to March 2012 were examined using a whole body counter within 2 months after they left Fukushima.

**Result:** <sup>131</sup>I was only detected in April while <sup>134</sup>Cs and <sup>137</sup>Cs were found up to November 2011. The maximum committed effective dose and thyroid equivalent dose were 22.4 μSv and 0.4 mSv, respectively, which were observed in April 2011. The internal radioactivity was found in almost all of the interior and the coastal regions regardless of the distance from the Fukushima-Daiichi nuclear power plant. Comparison of internal doses evaluated by the whole body counter and by prediction from environmental radioactivity indicates that the intake of radioactivity in March, April and possibly May 2011, would be mainly attributable to the inhalation of airborne radioactive particles, whereas in June and later months ingestion of contaminated food would be the major route of radioactive intake.

**Conclusion:** The risk for internal exposure existed for approximately six months after the radiological accident in almost the entire area of Fukushima, however, adverse health consequences by the radiation dose due to internal exposure seem to be negligible.

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## INTRODUCTION

The Great East Japan Earthquake and Tsunami on March 11, 2011 severely damaged the cooling functions of the reactor core in the Tokyo Electric Power Company (TEPCO) Fukushima Daiichi nuclear power plant. That accident resulted in the release of a large amount of radioactive materials, the radioactive contamination of a wide area of eastern Japan, and increased the risk for internal radiation exposure in residents of the area [1,2]. The early thyroid dose estimations conducted using a NaI(Tl) scintillation survey meter [3] and a scintillation spectrometer [4] demonstrated that the thyroid dose of all adults and children did not exceed 100 mSv. The committed

effective dose estimated by whole body scanning in our previous study [5] and by a urine bioassay [6] reported that the maximum dose from radiocesium in adults was 1.0 mSv and 0.1 mSv, respectively. These results suggest that the probability of initial internal radiation exposure among Fukushima residents at doses that could induce any deterministic or stochastic health effects is low.

The internal dose by an additional intake of radionuclides from contaminated foods in preexisting exposure situations has been estimated, mainly using a whole body counter (WBC). The examinations, carried out from September 2011 to March 2013 for 9,498 persons in Minami-soma city, detected only one

person who showed a committed effective dose higher than 1 mSv [7]. A survey at the Hirata Central Hospital demonstrated that  $^{137}\text{Cs}$  body burdens of 1,383 children were below the detection limit of 300 Bq/body in the fall of 2012 [8]. According to official statistics of the Fukushima prefecture, the number of residents with an internal dose of 1 mSv or higher was 26 out of 145,306 who received whole body examinations between June 2011 and July 2013 [9].

In Nagasaki, which is approximately 1,200 km southwest of Fukushima, direct measurements of internal radioactivity with a WBC in a low background environment have been performed since March 16, 2011 for people who stayed in Fukushima for different reasons. The total number of subjects examined exceeded 1,000 as of August 2013. Most of them belong to local governments, companies and hospitals in Nagasaki, and they were dispatched to Fukushima for support activities for a fixed period. Therefore, their internal radioactivity might reflect the radiological environment where they stayed for a certain period of time. Here, we have analyzed the internal doses of them in an attempt to estimate the chronological changes of health risk in Fukushima.

## **METHODS**

### **Subjects**

The subjects enrolled in this study were dispatched to the Fukushima prefecture at any time from April 2011 to March 2012 and received a whole body examination within 2 months after leaving Fukushima. The number of subjects was 372, which included 291 males and 81 females. The average age was 39.5 years old. Before entering the shielded room, each subject was asked to change his/her clothes to an examination gown. No contaminations were observed on their surface by a GM-survey meter.

### **Measurement of internal radioactivity by a WBC**

The horizontal bed-type WBC scanner at the Nagasaki University Medical School is equipped with two NaI(Tl) scintillation radiation detectors (8 inches in diameter and 4 inches in thickness) in the upper and lower positions. The whole detection unit is protected from naturally occurring external radiation by a shielded room covered with 20 cm-thick steel and 3 mm-thick lead layers. The two detectors synchronously scan the whole body of each subject longitudinally in 20 minutes at a constant linear speed. Signals from the detectors are processed in photomultipliers and are finally converted to information about the radionuclide species and their radioactivity by a multi-channel analyzer of the gamma-ray energy spectrum equipped with

preinstalled gamma analysis and calibration software (Fuji Electric #A212-173). The minimum detectable radioactivity (MDA) for  $^{131}\text{I}$ ,  $^{134}\text{Cs}$  and  $^{137}\text{Cs}$  was 30 Bq, 33 Bq and 33 Bq, respectively. The overall system was configured and assembled by Fuji Electric, Tokyo, Japan.

### **Dose estimation**

The internal radioactivity of each subject was used to estimate the initial intake of radionuclides according to two different scenarios, i.e., acute inhalation of particulate aerosol (AMAD=1  $\mu\text{m}$ ) with absorption type F on the first and on the last day of their stay in Fukushima, and chronic ingestion from the first and from the last day of their stay. Since the exact kinetics of intake for each subject were not available, the true value is expected to be within the range of these estimates. The committed effective dose and thyroid equivalent dose were then evaluated. All calculations were performed using MONDAL3 software [10] developed and distributed by the National Institute of Radiological Sciences, Japan, in which the essential parameters, reported in ICRP publications 30, 56, 66, 67, 69 and 71, and an additional database of dose coefficients [11] are preinstalled.

### **Prediction of internal dose from environmental radioactivity**

Besides the direct measurement using a WBC, the internal radioactivity by inhalation and by ingestion were predicted based on the environmental monitoring data on the airborne radioactivity of  $^{131}\text{I}$ ,  $^{134}\text{Cs}$  and  $^{137}\text{Cs}$  in several regions of the Fukushima prefecture [12] and on radioactive contamination of foodstuffs [13], respectively. The amount of radioactivity by inhalation was calculated by the ventilation rate at 20  $\text{m}^3/\text{day}$ , whereas the dose by ingestion was estimated on an assumption of a daily 100 g intake of contaminated foods for one month. The committed effective dose was evaluated using dose coefficients from inhalation and ingestion specified in publication 71 [14] and publication 67 [15] released by the ICRP.

## **RESULTS**

### **Internal dose estimation in chronological order**

The subjects were categorized according to the month when they started staying in Fukushima. Table 1 summarizes the number of subjects by month and the rate of detection of internal  $^{131}\text{I}$ ,  $^{134}\text{Cs}$  and  $^{137}\text{Cs}$ .  $^{131}\text{I}$  was only detected in April 2011 in 4 out of 71 persons (5.6% detection rate). The detection rate of  $^{134}\text{Cs}$  and  $^{137}\text{Cs}$  in April was 39.4% and 23.9%, respectively, and then decreased to 7% for both radionuclides in

May 2011. Although a clear time-dependent reduction of the detection rate was not observed, no radiocesium was found in subjects who were dispatched to Fukushima in December 2011. The average, median and range of internal radioactivity in subjects with <sup>131</sup>I, <sup>134</sup>Cs and <sup>137</sup>Cs are shown in Table 2. The average radioactivity was about twice as high as the detection limit of the WBC for each radionuclide. The maximum radioactivity was 233.0 Bq/body for <sup>134</sup>Cs in a subject who was dispatched to Fukushima in May. As shown in Table 3, the estimated maximum intake of radioactivity was 2,600 Bq/body for <sup>131</sup>I in April, 1,500 Bq/body for <sup>134</sup>Cs in May and 840 Bq/body for <sup>137</sup>Cs in May. All of these maximum estimations were given by the scenario of acute inhalation. Table 4 shows the committed effective dose induced by the intake of <sup>131</sup>I, <sup>134</sup>Cs and <sup>137</sup>Cs, and the sum of them. Because of the contribution of the <sup>131</sup>I dose to the total dose, the maximum dose, 22.4

μSv, was seen in April 2011. As the dose coefficient of the thyroid equivalent dose for adults is 20 times as large as the committed effective dose [14], the maximum thyroid equivalent dose was evaluated as approximately 0.4 mSv. From May onward, the total committed effective dose was less than 10 μSv for most of the subjects.

**Location and length of stay of subjects with internal radioactivity**

Figure 1 illustrates the locations where the internal radioactivity was detected and the number of subjects with or without internal radioactivity at each site. Although the total number of subjects differs largely for each location, internal radioactivity was found in almost the entire interior (Naka-dori) and coastal (Hama-dori) regions regardless of the distance from the Fukushima-Daichi nuclear power plant.

**Table 1.** Detection of internal <sup>131</sup>I, <sup>134</sup>Cs and <sup>137</sup>Cs in persons who were dispatched to Fukushima from April 2011 to March 2012 by WBC examination

Year	Month of dispatch	Number of subjects	Average days of stay (range)	<sup>131</sup> I		<sup>134</sup> Cs		<sup>137</sup> Cs		
				Number of detected	Detection rate (%)	Number of detected	Detection rate (%)	Number of detected	Detection rate (%)	
2011	Apr	71	12.4 (1-101)	4	5.6	28	39.4	17	23.9	
	May	71	13.0 (3-91)	0	0	5	7.0	5	7.0	
	Jun	64	9.8 (2-32)	0	0	4	6.3	0	0	
	Jul	42	11.4 (7-33)	0	0	0	0	0	0	
	Aug	41	25.2 (5-272)	0	0	8	19.5	3	7.3	
	Sep	20	18.7 (14-62)	0	0	1	5.0	0	0	
	Oct	6	45.5 (13-154)	0	0	0	0	0	0	
	Nov	14	39.9 (13-64)	0	0	1	7.1	1	7.1	
	Dec	4	13.0 (13-13)	0	0	0	0	0	0	
	2012	Jan	21	37.8 (2-89)	0	0	0	0	0	0
		Feb	11	25.7 (12-60)	0	0	0	0	0	0
		Mar	7	15.7 (11-29)	0	0	0	0	0	0
<b>Total</b>	<b>372</b>	<b>22.3 (1-272)</b>	<b>4</b>	<b>1.1</b>	<b>47</b>	<b>12.6</b>	<b>26</b>	<b>7.0</b>		

**Table 2.** Radioactivity in subjects with internal <sup>131</sup>I, <sup>134</sup>Cs or <sup>137</sup>Cs (Bq/body)

Month of dispatch	<sup>131</sup> I			<sup>134</sup> Cs			<sup>137</sup> Cs		
	Average	Median	Range	Average	Median	Range	Average	Median	Range
Apr	67.9	63.0	57.8-87.9	60.2	59.0	31.5-106.0	67.3	62.3	43.7-97.3
May	—	—	—	87.3	50.5	44.9-233.0	69.1	50.5	44.9-142.0
Jun	—	—	—	43.7	44.1	36.2-50.4	—	—	—
Jul	—	—	—	—	—	—	—	—	—
Aug	—	—	—	52.5	50.3	42.4-64.3	45.8	46.1	45.0-46.4
Sep	—	—	—	80.7	80.7	80.7-80.7	—	—	—
Oct	—	—	—	—	—	—	—	—	—
Nov	—	—	—	77.5	77.5	77.5-77.5	77.5	77.5	77.5-77.5

**Table 3.** Range of estimated intake of <sup>131</sup>I, <sup>134</sup>Cs or <sup>137</sup>Cs by the scenario of acute inhalation and chronic ingestion (Bq/body)

Month of dispatch	<sup>131</sup> I		<sup>134</sup> Cs		<sup>137</sup> Cs	
	Acute inhalation	Acute inhalation	Chronic ingestion	Acute inhalation	Chronic ingestion	
Apr	560 - 2,600	82 - 520	NT	130 - 460	NT	
May	—	160 - 1,500	NT	160 - 840	NT	
Jun	—	110 - 180	NT	—	NT	
Jul	—	—	NT	—	NT	
Aug	—	140 - 340	51 - 88	160 - 180	57 - 58	
Sep	—	210 - 420	110 - 110	—	—	
Oct	—	—	—	—	—	
Nov	—	380 - 580	160 - 160	370 - 520	150 - 150	

**Table 4.** Range of committed effective dose by exposure to <sup>131</sup>I, <sup>134</sup>Cs, <sup>137</sup>Cs and the sum of them by the scenario of acute inhalation and chronic ingestion (μSv)

Month of dispatch	<sup>131</sup> I		<sup>134</sup> Cs		<sup>137</sup> Cs		Total	
	Acute inhalation	Acute inhalation	Chronic ingestion	Acute inhalation	Chronic ingestion	Acute inhalation	Chronic ingestion	
Apr	4.2 - 19.0	0.5 - 3.4	NT	0.6 - 2.1	NT	0.5 - 22.4	NT	
May	—	1.0 - 9.9	NT	0.7 - 3.9	NT	1.7 - 13.8	NT	
Jun	—	0.8 - 1.2	NT	—	NT	0.8 - 1.2	NT	
Jul	—	—	NT	—	NT	—	NT	
Aug	—	0.9 - 2.3	1.0 - 1.7	0.8 - 0.8	0.7 - 0.8	0.9 - 2.5	1.0 - 2.4	
Sep	—	1.4 - 2.7	2.1 - 2.1	—	—	1.4 - 2.7	2.1 - 2.1	
Oct	—	—	—	—	—	—	—	
Nov	—	2.5 - 3.8	3.0 - 3.0	1.7 - 2.4	1.9 - 1.9	4.2 - 6.2	4.9 - 4.9	

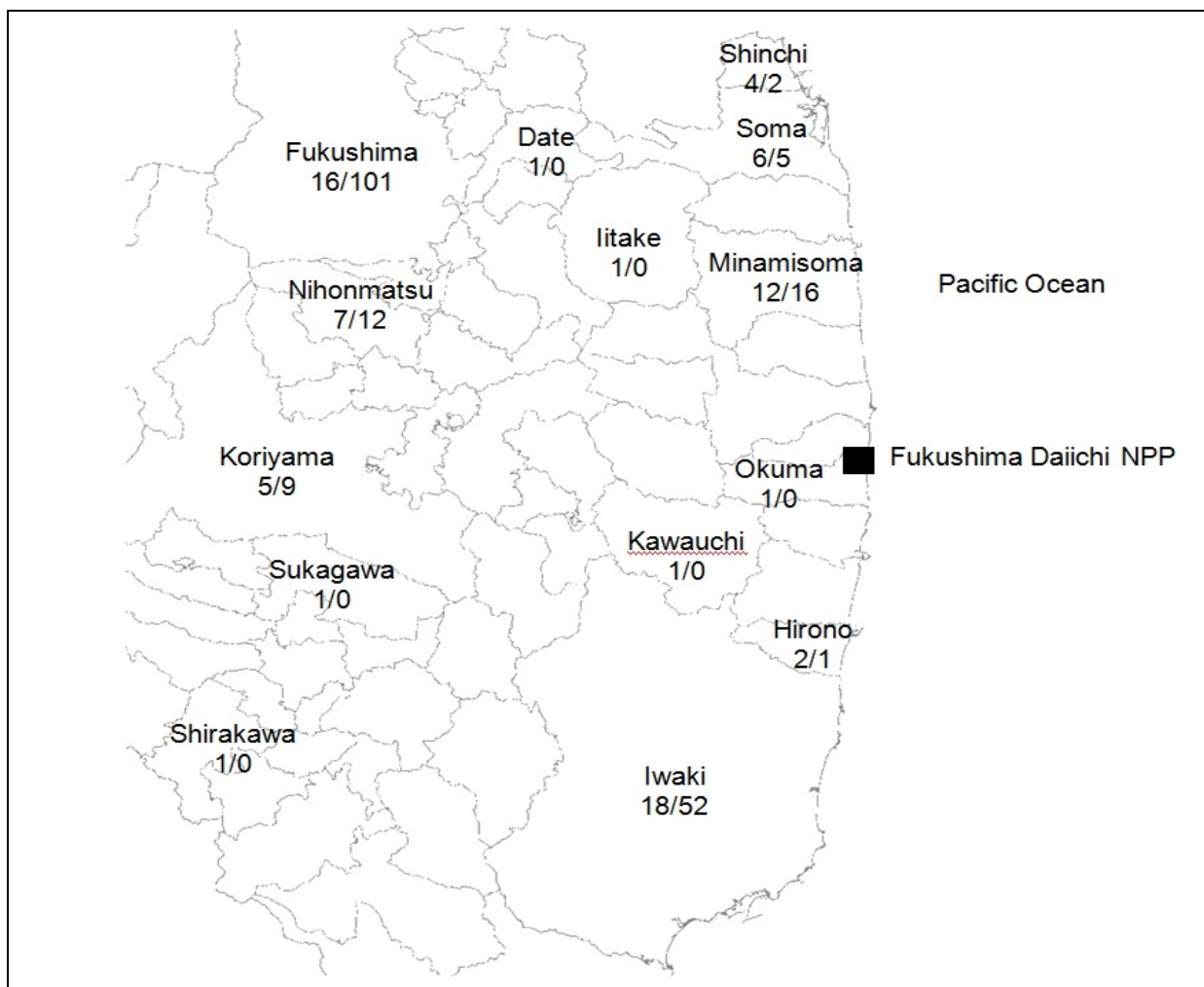


Figure 1. Location where the internal radioactivity was detected. Upper line: name of city, town, village. Lower line: number detected/undetected.

Table 5. Comparison of internal doses predicted from environmental radioactivity and direct measurement by the WBC ( $\mu\text{Sv}$ )

		2011								2012			
		Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
Prediction by inhalation of environmental airborne radioactivity	Fukushima	14.1	-	-	-	-	0.1	-	-	-	-	-	-
	Iwaki	18.1	-	-	1.3	1.0	1.0	0.6	1.2	-	-	0.1	-
	Minami soma	41.0	9.9	-	-	1.0	-	-	-	-	-	-	-
Prediction by ingestion of radioactive contaminated foodstuffs		68.6	25.5	30.8	10.9	7.5	13.7	2.5	6.8	9.1	1.8	27.8	1.2
WBC examination	Acute inhalation	22.4	13.8	1.2	-	2.5	2.7	-	6.2	-	-	-	-
	Chronic ingestion	NT	NT	NT	-	2.4	2.1	-	4.9	-	-	-	-

### **Comparison of internal doses evaluated by a direct measurement and by prediction from environmental radioactivity**

Table 5 summarizes the predicted internal doses due to the inhalation of environmental airborne radioactivity and the ingestion of radioactive contaminated foods. The contribution of the ingestion of foods to the committed effective dose was always higher than that of the inhalation of airborne radioactivity. The maximum internal dose determined by the whole body examination was lower than the dose by ingestion and was within the range of doses by inhalation in April and May 2011. In June and following months, the dose predicted from the airborne radioactivity was markedly reduced while that from contaminated foods remained. The direct measurement showed the maximum dose at a level closer to the dose by ingestion.

### **DISCUSSION**

We have previously reported that internal  $^{131}\text{I}$  was detected in approximately 30% of first responders and evacuees within one month after the Fukushima radiological accident in March 2011 [5]. In this study,  $^{131}\text{I}$  was found in only four subjects who were in Fukushima in April 2011. These data suggest that the possible uptake of  $^{131}\text{I}$  was limited in March and April in normal living environments. In contrast, internal  $^{134}\text{Cs}$  and  $^{137}\text{Cs}$  were detected up to November at radioactivity levels ranging from 31.5 Bq to 233 Bq per body. Extensive examinations of internal radioactivity in Fukushima started in September, 2011 by a WBC of the minimal detection activity at 300 Bq/body [7], which was much higher than the usual situation because of the high background radiation even in the examination room. Therefore, the exact nature of internal radioactivity below 300 Bq has not been clarified. Our results may provide evidence that the internal radioactivity from the environment, including contaminated foods, after June 2011 did not exceed 80.7 Bq by the largest estimation. When we consider that the biological half-life of cesium is approximately 70 days, it would be reasonable to conclude that the sum of internal radioactivity from initial and additional intakes did not reach 300 Bq at time measurements later than September 2011.

The chronological changes in the intake route of radioactive substances also should be taken into consideration. In early evacuees, our previous study demonstrated that the difference in actual internal radioactivity assessed by a WBC among individuals roughly agreed with the difference in the estimated airborne radioactivity estimated from atmospheric dispersion simulations [16]. In this study we also

found that the maximum internal radioactivity as measured directly was almost at a level similar to the predicted radioactivity from airborne monitoring data in April and May 2011. As control of contaminated food has been in effect since March 17, 2011 [17], the intake of radioactivity in March, April and possibly May, would be mainly attributable to the inhalation of airborne radioactive particles. Thereafter, the measured internal radioactivity of subjects in June or later months became much closer to the activity predicted by the ingestion model of contaminated foods, not by the inhalation model. Since those subjects did not undergo early internal exposure by inhalation, the ingestion of foods with radioactivity below the regulated level [18] and the inhalation of contaminated particles re-suspended from the ground might have accumulated and gone beyond the detection level of the WBC. Individual dietary habits, such as a preference for homegrown vegetables rather than commercially distributed foods, would also affect the risk for intake of radioactivity. However, these issues were not addressed in our survey.

The maximum committed effective dose and thyroid equivalent dose, 22.4  $\mu\text{Sv}$  and 0.4 mSv, respectively, were observed in April 2011 by the scenario of acute inhalation. Both doses are well below the annual dose limit for the public and below the level to consider treatment with stable iodine to prevent iodine uptake by the thyroid gland, and therefore, the induction of health risk by internal exposure in our subjects seems negligible. Nevertheless, it should be noted that the possibility of internal exposure existed, even in temporary residents within approximately six months after the radiological accident, over almost the entire area in Fukushima.

Two years have now passed since the accident, but the ambient radiation dose in many parts of Fukushima is still higher than 1 mSv/year, the long-term goal of decontamination [19]. Environmental samples, such as soils, sands and fallen leaves, contain detectable levels of radioactivity. However, the radioactivity that was taken into the body two years ago may be represented by the results in this study. A recent report on the internal exposure of decontamination workers in heavily contaminated areas around the Fukushima Daiichi nuclear power plant has shown that the WBC examination did not find any detectable radioactivity in 83 subjects before March 2012 [20]. Taken together, the present risk for internal exposure is quite low in a normal living situation.

### **CONCLUSION**

Internal  $^{131}\text{I}$  was only detected in April while  $^{134}\text{Cs}$  and  $^{137}\text{Cs}$  were found up to November, 2011 in 372

subjects who were dispatched to the Fukushima prefecture at any time from April 2011 to March 2012. The maximum committed effective dose and thyroid equivalent dose were 22.4  $\mu$ Sv and 0.4 mSv, respectively. A risk for internal exposure existed approximately six months after the radiological accident over almost the entire area of Fukushima, however, adverse health consequences by the radiation dose due to internal exposure seems to be negligible for these subjects.

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