Internal radiocesium contamination of adults and children in Fukushima 7 to 20 months after the Fukushima NPP accident as measured by extensive whole-body-counter surveys

By Ryugo S. HAYANO,[*1,†] Masaharu TSUBOKURA,[*2] Makoto MIYAZAKI,[*3] Hideo SATOU,[*4] Katsumi SATO,[*4] Shin MASAKI[*4] and Yu SAKUMA[*4]

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Abstract: The Fukushima Dai-ichi NPP accident contaminated the soil of densely-populated regions in Fukushima Prefecture with radioactive cesium, which poses significant risks of internal and external exposure to the residents. If we apply the knowledge of post-Chernobyl accident studies, internal exposures in excess of a few mSv/y would be expected to be frequent in Fukushima.

Extensive whole-body-counter surveys ($n = 32{,}811$) carried out at the Hirata Central Hospital between October, 2011 and November, 2012, however show that the internal exposure levels of residents are much lower than estimated. In particular, the first sampling-bias-free assessment of the internal exposure of children in the town of Miharu, Fukushima, shows that the ^{137}Cs body burdens of all children ($n = 1{,}383$, ages 6–15, covering 95% of children enrolled in town-operated schools) were below the detection limit of 300 Bq/body in the fall of 2012. These results are not conclusive for the prefecture as a whole, but are consistent with results obtained from other municipalities in the prefecture, and with prefectural data.

Keywords: Fukushima Dai-ichi NPP accident, radioactive cesium, whole-body counting, committed effective dose

1. Introduction

The severe accident involving the Fukushima Dai-ichi nuclear power plant (NPP),[1] triggered by the Great East Japan Earthquake and resulting Tsunami on March 11, 2011, dispersed large amounts of radionuclides, which were deposited on soil and water in Fukushima Prefecture and surrounding regions of Japan. A recent airborne monitoring survey[2] carried out by the Japanese government (Fig. 1) shows that the surface deposition density of ^{137}Cs amounts to 60 k–300 kBq/m^2 in such densely populated cities as Fukushima (population ≈280,000) and Koriyama (population ≈330,000).

Post-Chernobyl accident studies show that the level of internal radiation exposure of residents from ingestion of contaminated foodstuffs is nearly proportional to the deposition density; according to the UNSCEAR 1988 report on the exposures from the Chernobyl accident,[3] the mean transfer factor from ^{137}Cs deposition density (kBq/m^2) to first-year committed effective dose (µSv/y) for adults is about 20. If this also applies to the Fukushima Dai-ichi case, the committed effective dose (CED) would be about 2 mSv (*i.e.*, average daily intake of ^{137}Cs ≈400 Bq/day, or body burden of ≈60,000 Bq/body, or body concentration of ≈800–900 Bq/kg) for adults living in the region where the ^{137}Cs deposition density is ∼100 kBq/m^2 (typical of Fukushima City).

Note that the airborne monitoring surveys[4] and the soil sample analyses[5] have shown that the ratios of deposition amounts of ^{134}Cs (half life

[*1] Department of Physics, The University of Tokyo, Tokyo, Japan.[‡]
[*2] Division of Social Communication System for Advanced Clinical Research, Institute of Medical Science, The University of Tokyo, Tokyo, Japan.[‡]
[*3] Department of Radiation Health Management, Fukushima Medical University, Fukushima, Japan.[‡]
[*4] Hirata Central Hospital, Fukushima, Japan.[‡]
[†] Correspondence should be addressed: R. Hayano, Department of Physics, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan (e-mail: hayano@phys.s.u-tokyo.ac.jp).
[‡] Research institute of radiation safety for disaster recovery support, Hirata village, Fukushima, Japan.

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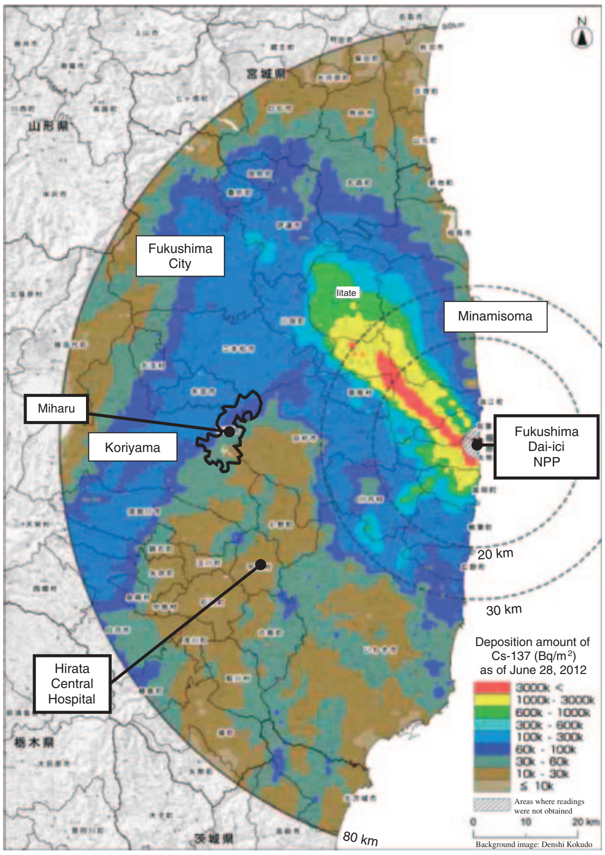

Fig. 1. Deposition amount of ^{137}Cs on the ground surface within a 80 km radius of the Fukushima Dai-ichi NPP (fifth airborne monitoring survey, as of June 28, 2012).[2)]

$T_{1/2} = 2.1$ y) against those of ^{137}Cs ($T_{1/2} = 30$ y) in soil samples, extrapolated back to March 2011, were about 1 : 1, so that the actual CED due to radioactive cesium in Fukushima would be higher by a factor of ~2.5 than the 2 mSv estimate from ^{137}Cs alone.

There are already several indications that the actual CEDs of Fukushima residents are much lower than estimated above, one being the whole-body counting conducted by the Fukushima prefectural government, starting in late June 2011.

So far, >100,000 residents have been screened with whole-body counters (WBC), and >99.9% of them showed a CED of less than 1 mSv (the sum of the contributions from ^{134}Cs and ^{137}Cs together),[6)] as summarized in Table 1. Here, column A shows the statistics of the whole period from June, 2011 to December, 2012; column B shows results through the end of January, 2012; and column C those obtained after February 1st, 2012. The reason for dividing the data into two parts, B and C, is that there was a

Table 1. WBC statistics published by the Fukushima Prefectural Government on January 31, 2013[6)]

	A	B	C
< 1 mSv	106,070	15,383	90,687
1–2 mSv	14	13	1
2–3 mSv	10	10	0
> 3 mSv	2	2	0
Total	106,096	15,408	90,688

change in the model assumption when calculating the CED from the amount of radioactive cesium in the body. Namely, for exposures incurred between March, 2011 and the end of January, 2012, the calculations assumed acute inhalation of radioactive cesium in March, 2011, while constant daily intake of radioactive cesium throughout the year was assumed for exposures incurred after February, 2012 (please note, at the time of this writing, the Fukushima Prefectural Government has not yet released the WBC survey breakdown in Bq/kg or Bq/body, nor indicated how many subjects showed non-detection).

The fact that the CEDs were less than 1 mSv in all but 1 resident after February, 2012 already indicates that the average daily intake of radioactive cesium by Fukushima residents must be less than estimated from the deposition density. In fact, the actual intake is significantly less, as will be presented below.

2. Methods

We measured the amount of radioactive cesium in the bodies of residents of Fukushima and surrounding prefectures with whole body counter systems (Fastscan Model 2251, Canberra Inc.) installed at the Hirata Central Hospital in Fukushima Prefecture, located 45 km southwest of Fukushima Dai-ichi NPP. The study was approved by the Ethics Committee of the University of Tokyo. The detection limits were 300 Bq/body for both ^{134}Cs and ^{137}Cs following a 2-minute scan. For subjects shorter than 110 cm in height, a platform of 20 cm was used to adjust the height, and for those between 110 cm and 125 cm, a platform of 12 cm was used, as recommended by the manufacturer. The subjects were screened for surface contamination using a hand-held survey meter (model TGS-146B, Hitachi Aloka Medical, Ltd.) before whole-body counting, and initially were required to change into a hospital gown only if such contamination was detected. After

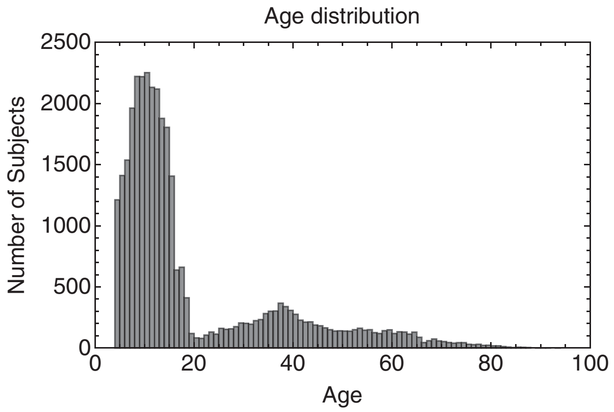

Fig. 2. The age distribution of the residents enrolled in this study (range 4–93, median 12, mean 19).

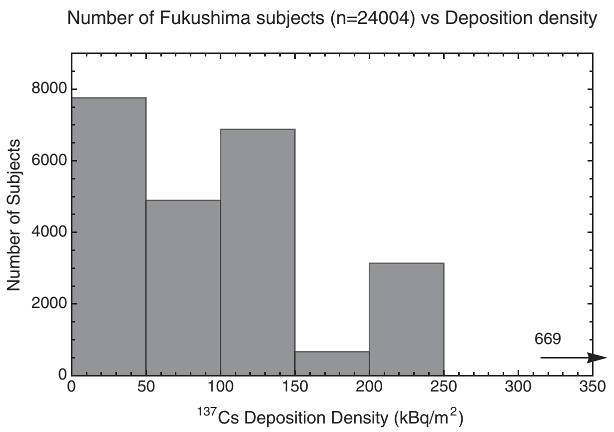

Fig. 3. The distribution of the number of subjects in Fukushima vs the deposition density of ^{137}Cs (kBq/m^2).

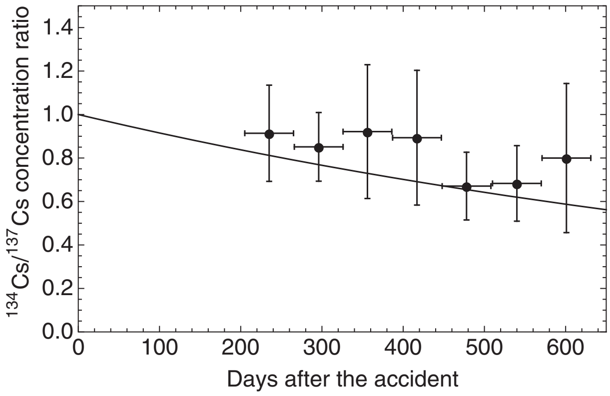

Fig. 4. The ratio of ^{134}Cs to ^{137}Cs body concentrations plotted against the number of days after the Fukushima Dai-ichi accident. The solid curve is calculated by assuming an initial ^{134}Cs/^{137}Cs ratio of 1 : 1.

March 1, 2012, all subjects changed into a hospital gown regardless of their surface screening results.

The results presented below are based on the data obtained from October 17, 2011 until November 30, 2012. A total of 32,811 people were measured during this period, and their age distribution is as shown in Fig. 2.

Of the 32,811 subjects, 73% were from Fukushima Prefecture, and 23% were from Ibaraki Prefecture; smaller numbers were from Tochigi and Miyagi Prefectures (all adjacent to Fukushima). Figure 3 shows the distribution of number of subjects in Fukushima versus the deposition density of ^{137}Cs.[7)]

Note that this dataset is not included in the aforementioned whole-body counting results published by the Fukushima Prefectural Government, and described in Table 1, which end in December, 2012.

3. Results

A. Overview. The measured ratio of ^{134}Cs to ^{137}Cs body concentration is nearly 1 : 1, and is gradually decreasing over time as shown in Fig. 4. For the sake of brevity, hereafter we report only the ^{137}Cs concentration.

Table 2 shows statistics for the results of whole-body counting for all subjects (columns 2–4) and for children under age 15 (columns 5–7). The numbers of people whose body content of ^{137}Cs exceeded the detection limit of 300 Bq/body are shown in columns 3 and 6, and their percentages in columns 4 and 7.

The whole-body counting carried out in Minamisoma city between September 26, 2011 and March 31, 2012 (Tsubokura *et al.*[8)]) showed that 34.6% of the residents had detectable levels of cesium, but the body concentrations were much lower than those reported in studies years after the Chernobyl accident[9)–11)] (the CEDs being less than 1 mSv in all but 1 resident (1.07 mSv)).

The percentage of subjects in which cesium was detected at Hirata during this period (Table 2) was smaller than in Minamisoma City, but also note that there is a sharp decrease in the ^{137}Cs detection percentages after March 2012, in particular among children, when the policy of having every subject change into a hospital gown was instituted. This is further illustrated in Fig. 5.

This indicates that while some 15% of subjects may have inhaled/ingested radioactive cesium in the early phase of the accident, a part of the Cs-positive results obtained during the first 5 months may have

Table 2. Results of WBC screening conducted at Hirata Central Hospital from Oct., 2011 through Nov., 2012. Columns 2–4 are for all subjects, and columns 5–7 are for children age 15 and under only. The numbers of people whose body burden of ^{137}Cs exceeded the detection limit of 300 Bq/body are shown in columns 3 and 6, and their percentages in columns 4 and 7

Month, Year	All			Children (age ≤ 15)		
	n	n_{det} (^{137}Cs)	n_{det}/n (%)	n	n_{det} (^{137}Cs)	n_{det}/n (%)
Oct., 2011	638	76	12.0	312	33	10.6
Nov., 2011	2,258	327	15.0	970	85	8.8
Dec., 2011	2,338	352	15.0	1,456	133	9.1
Jan., 2012	2,843	341	12.0	1,665	123	7.4
Feb., 2012	2,949	244	8.3	1,907	113	5.9
subtotal $\sum_{\text{Oct.,2011}}^{\text{Feb.,2012}}$	11,026	1,340	12.1	6,310	487	7.7
Mar., 2012	3,572	113	3.2	1,821	9	0.5
Apr., 2012	3,043	44	1.4	1,162	3	0.3
May, 2012	1,056	13	1.2	321	0	0.0
Jun., 2012	1,776	13	0.7	1,079	0	0.0
Jul., 2012	2,325	6	0.3	1,236	0	0.0
Aug., 2012	1,979	10	0.5	1,223	0	0.0
Sep., 2012	2,416	1	0.0	1,804	0	0.0
Oct., 2012	3,237	1	0.0	2,736	0	0.0
Nov., 2012	2,381	11	0.5	1,838	0	0.0
subtotal $\sum_{\text{Mar.,2012}}^{\text{Nov.,2012}}$	21,785	212	1.0	13,220	12	0.09
Total	32,811	1,552	4.7	19,530	499	2.6

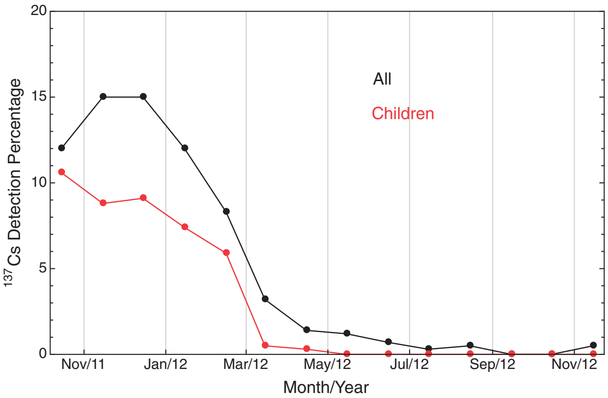

Fig. 5. The temporal changes of the ^{137}Cs detection percentages for all subjects (black) and children (red).

been due to surface (clothes) contamination which escaped the survey meter screening.

As we cannot accurately quantify the surface contamination effect, we restrict ourselves here to the analyses of the data taken after March 2012. The results presented in Table 2 and Fig. 6 indicate the following:

1. The internal exposure level of Fukushima residents is much less than was estimated from the deposition density.
2. This is particularly true for children. After May 2012, ^{137}Cs was not detected in children ($n = 10{,}237$). Assuming a constant daily intake, and from the detection limit of 300 Bq/body, the maximum CEDs estimated using Mondal 3 software[12] is 21 µSv/y (age ~10) and 13 µSv/y (age ~15). In terms of daily intake of ^{137}Cs, these CEDs correspond to 5.8 Bq/day and 2.7 Bq/day, respectively. These are again much lower than estimated from the deposition density.
3. High cesium concentrations (maximum: 184 Bq/kg of ^{137}Cs and 108 Bq/kg of ^{134}Cs, CED = 1.06 mSv) were found in a small number of senior residents (Table 3). We used a germanium semiconductor detector to measure the foodstuffs consumed by those subjects, and found that they regularly ate items for which contamination advisories have been issued such as wild mushrooms, wild boar, fresh-water fish, etc., which they harvested or caught themselves, or received from neighbors, but which were not tested for radioactive cesium. These subjects were advised again to avoid consuming such foodstuffs, whereupon their body burdens decreased at rates consistent with the biological half life of cesium.

It may be argued that the lower-than-expected CEDs could be the result of sampling biases, *e.g.*, those residents who take extreme care to avoid cesium-contaminated food are more likely to request WBC screening. This is in fact not the case, as we show in the next section.

B. Minimum-bias results—school children of Miharu town. The whole-body counting results of the school children of Miharu town (a subset of the data presented above) constitute a nearly sampling-bias-free dataset, as we made an agreement with the Miharu school board to examine the internal exposure of all children enrolled in town-operated elementary (age 6–12) and junior-high (age 12–15) schools.

Miharu (population ~18,000) is a suburban town located 50 km west of Fukushima Dai-ichi NPP (see Fig. 1). The percentage of agricultural households in Miharu is about 20%, while the ^{137}Cs deposition density ranges from 9,000 to 160,000

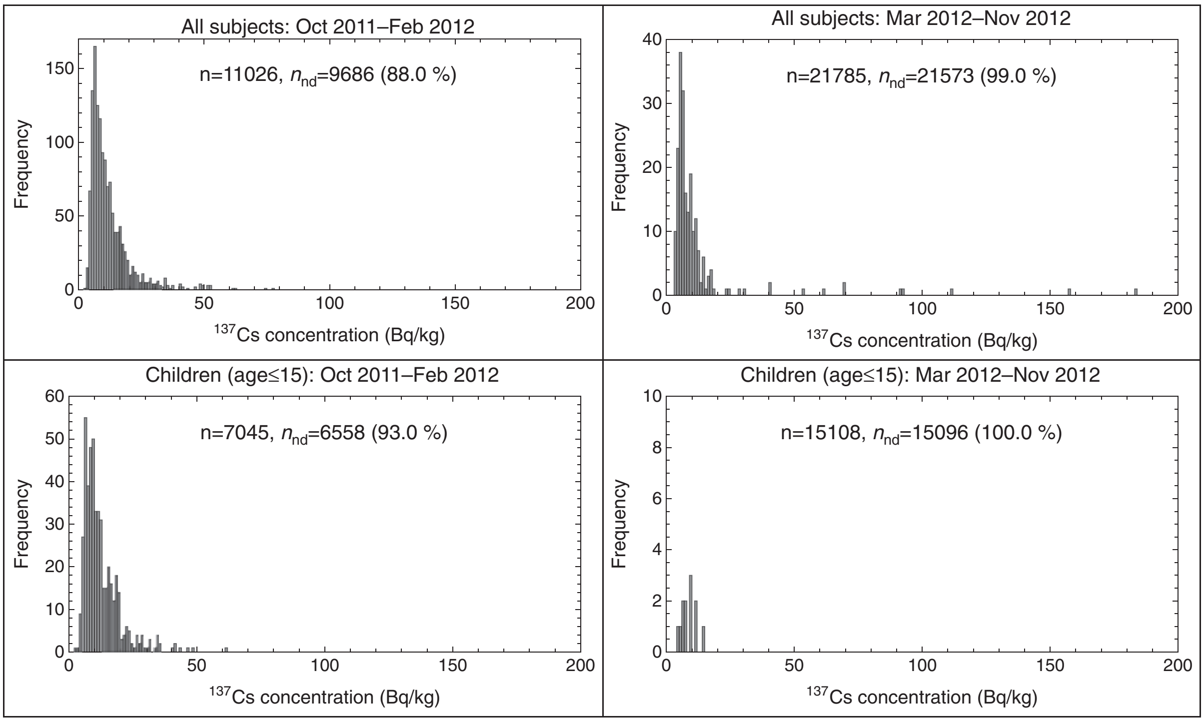

Fig. 6. ^{137}Cs concentration for all subjects (top) and for children only (bottom), in 1 Bq/kg increments. The right-hand panels are for the period when a change of clothes was instituted for all subjects to minimize spurious readings from surface contamination. Note the different ordinate scale for each panel. Nonexposed (non-detected) subjects are excluded from the plot.

Table 3. The four highest ^{137}Cs body burdens detected among Fukushima residents as of November, 2012

Age	Sex	Resident of	First measurement	^{137}Cs (Bq/body)	^{137}Cs (Bq/kg)	Second measurement	^{137}Cs (Bq/body)	^{137}Cs (Bq/kg)
74	M	Nihonmatsu	2012.8	12,270	183.7	2012.11	6,177	91.9
70	M	Kawamata	2012.7	7,032	111.6	2012.11	2,547	40.6
74	F	Nihonmatsu	2012.8	4,830	69.4	2012.11	2,139	30.3
66	F	Kawamata	2012.7	4,300	69.6	2012.11	1,485	23.9

Table 4. The statistics of Miharu-town school children (ages 6–15) WBC measurements. The numbers of children enrolled in schools were published by the school board of Miharu town, which may not match the actual numbers of children attending schools when the WBC measurements were carried out

Enrolled in August 25, 2011	Measured in Winter 2011	Coverage	^{137}Cs detected	Enrolled in April 1, 2012	Measured in Fall 2012	Coverage	^{137}Cs detected
1,585	1,494	94.3%	54	1,456	1,383	95.0%	0

Bq/m^2 (mean 80,000 Bq/m^2). Some Miharu residents are therefore potentially at high risk of internal exposure. We conducted two WBC screenings of children in Miharu. The first screening was conducted between November 24, 2011 and February 29, 2012, and included 1494 children; the second was conducted between September 3, 2012 and November 8, 2012, and included 1383 children. Coverage was 94.3% and 95.0% respectively (Table 4).

The results of the second screening show that in the fall of 2012, none of the 1383 children had a detectable level of radioactive cesium. In view of the

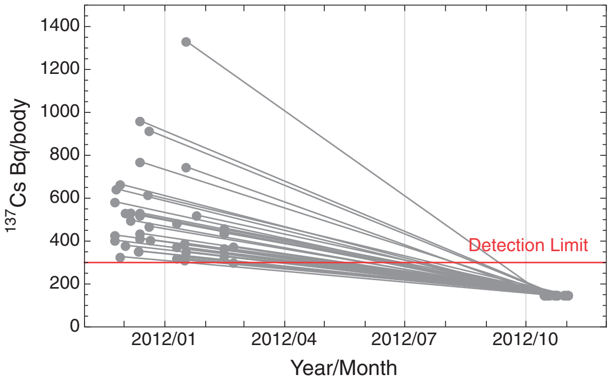

Fig. 7. ^{137}Cs body burden changes over time for 40 children who tested cesium-positive in the first screening in Miharu and were also enrolled in the second. A value of 150 Bq/body has been assigned to nonexposed data (non-detection). The connecting lines are for the sake of visualization.

high coverage of 95%, it is safe to conclude that the low level of internal exposure in Miharu is not due to sampling bias.

On the other hand, the first screening, in the winter of 2011–2012, found that 54 of the 1494 children were cesium-positive. Of these, 40 were enrolled in the second screening as well (14 others had graduated), and the temporal changes in their body burdens are shown in Fig. 7. As discussed above, some of the detections in the first measurements may have been caused by surface (clothes) contamination. We therefore do not further analyze these data.

4. Conclusions

The Fukushima Dai-ichi NPP accident contaminated the soil of densely-populated regions in Fukushima Prefecture with radioactive cesium, which poses significant risks of internal and external exposure to the residents. If we apply the transfer factor from deposition density to CED obtained from post-Chernobyl accident studies, internal exposures in excess of a few mSv/y would be expected to be frequent.

The whole-body-counter measurements carried out at the Hirata Central Hospital show that the internal exposure levels of residents are much lower than estimated. Between 12 to 20 months after the start of the Fukushima Dai-ichi NPP accident, the ^{137}Cs detection frequency was 1.0% (0.09% among children).

In the town of Miharu, where we measured 95% of the children (ages 6–15) enrolled in town-operated schools, the ^{137}Cs body burdens of all children were below the detection limit of 300 Bq/body in the fall of 2012. This is the first sampling-bias-free assessment of the internal exposure of children in Fukushima.

These results are not conclusive for the prefecture as a whole, but are consistent with results obtained from other municipalities in the prefecture, and with prefectural data. This does not mean, however, that Fukushima residents are free of internal exposure risks, as evidenced by a small number of senior citizens whose body burden exceeded 100 Bq/kg.

Although clarifying the reasons for the great differences in the estimated CEDs between Chernobyl and Fukushima, based on deposition density and the actual internal contamination found in our studies, is beyond the scope of the present paper, the results of duplicate-portion studies, *e.g.*, Ref. 13, indicate that proportion of food with high-enough radioactivities are rather low in Fukushima.

Conscientious and well-supervised food testing/screening and whole-body counting must be carried out continuously in Fukushima in order to maintain the low-level of internal exposure.

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