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COMMENTARY

Measurements of Individual Radiation Doses in Residents Living Around the Fukushima Nuclear Power Plant

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At the outset of the accident at Fukushima Daiichi Nuclear Power Plant in March 2011, the radiation doses experienced by residents were calculated from the readings at monitoring posts, with several assumptions being made from the point of view of protection and safety. However, health effects should also be estimated by obtaining measurements of the individual radiation doses. The individual external radiation doses, determined by a behavior survey in the “evacuation and deliberate evacuation area” in the first 4 months, were <5 mSv in 97.4% of residents (maximum: 15 mSv). Doses in Fukushima Prefecture were <3 mSv in 99.3% of 386,572 residents analyzed. External doses in Fukushima City determined by personal dosimeters were <1 mSv/3 months (September–November, 2011) in 99.7% of residents (maximum: 2.7 mSv). Thyroid radiation doses, determined in March using a NaI (TI) scintillation survey meter in children in the evacuation and deliberate evacuation area, were <10 mSv in 95.7% of children (maximum: 35 mSv). Therefore, all doses were less than the intervention level of 50 mSv proposed by international organizations. Internal radiation doses determined by cesium-134 (¹³⁴Cs) and cesium-137 (¹³⁷Cs) whole-body counters (WBCs) were <1 mSv in 99% of the residents, and the maximum thyroid equivalent dose by iodine-131 WBCs was 20 mSv. The exploratory committee of the Fukushima Health Management Survey mentions on its website that radiation from the accident is unlikely to be a cause of adverse health effects in the future. In any event, sincere scientific efforts must continue to obtain individual radiation doses that are as accurate as possible. However, observation of the health effects of the radiation doses described above will require reevaluation of the protocol used

for determining adverse health effects. The dose-response relationship is crucial, and the aim of the survey should be to collect sufficient data to confirm the presence or absence of radiation health effects. In particular, the schedule of decontamination needs reconsideration. The decontamination map is determined based on the results of airborne monitoring and the radiation dose calculated from readings taken at the monitoring posts at the initial period of the accident. The decontamination protocol should be reevaluated based on the individual doses of the people who desire to live in those areas. © 2013 by Radiation Research Society

INTRODUCTION

More than two years have passed since the accident at the Fukushima Daiichi Nuclear Power Plant, but scientific information on that accident has not yet been compiled (1–4). The assessment of radiation doses in the general population in Fukushima is important for evaluating the scale of the accident as well as the effectiveness of countermeasures taken by the local and central Japanese governments. In addition, the results of this assessment provide important and fundamental information for preparing future countermeasures. Radiation doses in the initial period after the accident were calculated from simple readings taken at monitoring points using several assumptions with respect to protection and safety. Information about individual radiation doses should be used immediately to estimate the health effects of radiation.

Various research institutes have reported (in Japanese) measurements of individual radiation doses of residents surrounding the Fukushima Daiichi Nuclear Power Plant at various times and places since the accident. Each research institute will present formal reports in English at a later date, but we, as members of Japanese scientific societies, have

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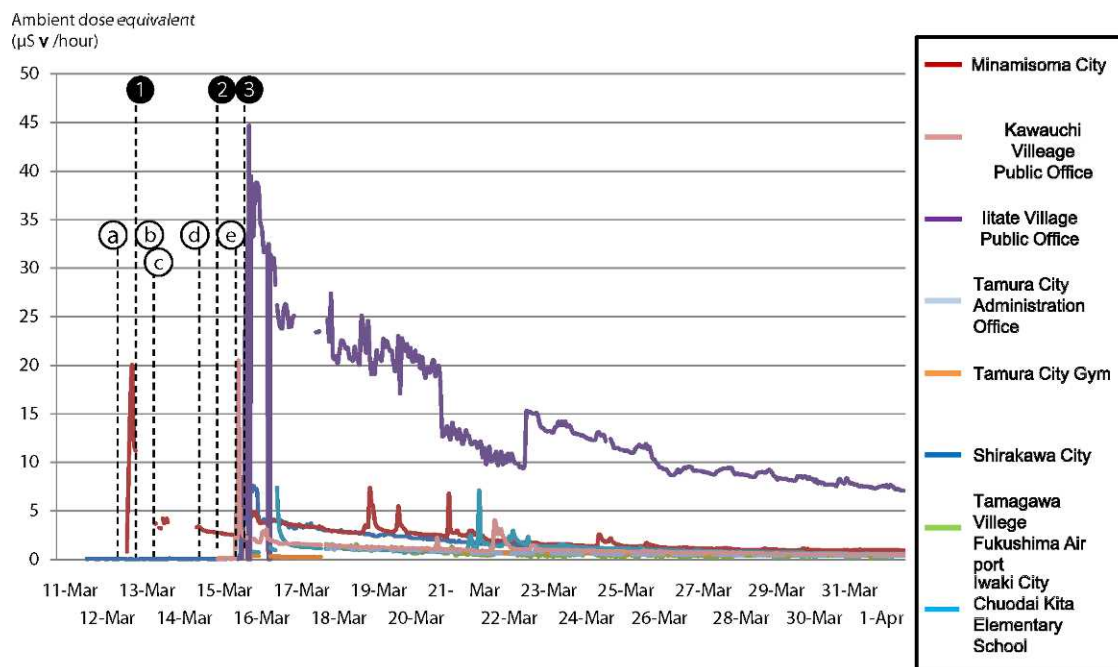


FIG. 1. The ambient dose equivalent around the nuclear power plant at the initial phase of the accident, recorded by monitoring devices that were not damaged by the earthquake or tsunami. The location of each city and village is indicated in Fig. 2a. 1. Hydrogen explosion at unit 1 at 15:36, March 12, 2011; 2. Hydrogen explosion at unit 3 at 11:01, March 14, 2011; 3. Hydrogen explosion at unit 4 at 06:14, March 15, 2011; a. Vent opened at unit 1 at 10:17, March 12, 2011; b. Vent opened at unit 3 at 08:41, March 13, 2011; c. Vent opened at unit 2 at 11:00, March 13, 2011; d. Vent opened at unit 3 at 05:20, March 14, 2011; and e. Vent opened at unit 2 at 00:02, March 15, 2011.

reviewed reports (mainly located on Japanese websites) on the estimation and the actual measurement of the individual radiation doses in residents. In this article, we present a brief summary of these measurements to worldwide specialists in the field of radiation research.

OUTLINE OF THE ACCIDENT AND ITS COUNTERMEASURES

On March 11, 2011, a 9.0-magnitude earthquake (the Great East Japan Earthquake) struck the east coast of Japan near Iwate, Miyagi and Fukushima Prefectures. Fifty minutes after the earthquake, a tsunami with a height over 15 m hit the Fukushima Daiichi Nuclear Power Plant, causing extensive damage to its cooling system and resulting in the loss of all power sources at the plant (4). Consequently, a radioactive plume from units 1–4 was dispersed into the atmosphere. Figure 1 shows the dose rates around the nuclear power plant at the initial phase of the accident, which were recorded by monitoring devices that had not been damaged by the earthquake or tsunami.

Instructions to evacuate or remain inside were issued to the local residents by the Director-General (Prime Minister) of the Nuclear Emergency Response Headquarters. This office was established on March 11, 2011, within the Cabinet of Japan, to organize this emergency response: At 20:50 on that day, residents who lived within a 2-km radius

of the plant were told to evacuate. This order was extended to a 3-km radius at 21:23 on that day, then to a 10-km radius on the morning of March 12, and then to a 20-km radius that afternoon. On March 14, Fukushima Prefecture performed ambient dose monitoring, and on March 15, those living within 20–30 km were instructed to take shelter inside their houses (5). On March 17, the government initiated “food control” to minimize internal radiation exposure, and all contaminated cow’s milk was disposed of. These decisions resulted in the evacuation of almost 110,000 people after the accident.

On April 22, 2011, the government designated a “deliberate evacuation area” where the annual cumulative radiation dose was predicted to reach 20 mSv (5). Chronological events during the initial phase of the accident are shown in Table 1. Many issues are currently being discussed, such as decontamination, health check-ups and the return of the population. To date, no victims or patients with acute radiation syndrome have been reported in the general population or among workers in the nuclear power plants.

ESTIMATION OF INDIVIDUAL EXTERNAL RADIATION DOSE FROM A BEHAVIOR SURVEY

The Fukushima Health Management Survey conducted by Fukushima Prefecture estimated the external radiation

TABLE 1
Chronological Events During the Initial Phase of the Accident at the FNPP

Date	Nuclear power plant accident/evacuation Orders/evacuation	Implemented policies on food control
March 11	20:50 – Evacuation order for residents within a 2-km radius 21:23 – Evacuation order within a 3-km radius 21:23 – Sheltering order within a 3–10-km radius	
March 12	0:30 – Complete evacuation of residents within a 3-km radius 5:44 – Evacuation instructions within a 10-km radius 15:36 – Unit 1: Hydrogen explosion 18:25 – Evacuation order within a 20-km radius	
March 14	11:01 – Unit 3: Hydrogen explosion	
March 15	6:14 – Unit 2: suppression chamber: Hydrogen explosion – Unit 4: Hydrogen explosion 10:00 – Evacuation of Namie Town recommended 11:00 – Sheltering order within a 20–30-km radius 14:00 – Complete evacuation of residents within a 20-km radius	
March 17		Establishment of provisional regulation values for ^{131}I (300 Bq/kg for drinking water and milk and 2,000 Bq/kg for vegetables, respectively), ^{134}Cs and ^{137}Cs (200 Bq/kg for drinking water and milk, 500 Bq/kg for vegetables, grains and meats, fishes and eggs, respectively).
March 21		Order to restrict shipping of food products exceeding provisional regulation values (hereafter, shipping restricted on products exceeding regulation values).
March 25	11:46 – Chief Cabinet Secretary announced an active voluntary evacuation of residents within a 20–30-km radius	
April 22	Establishment of a deliberate evacuation area and restricted area	

dose of residents based on their behavior. The National Institute of Radiological Sciences (NIRS) developed an external radiation evaluation system that estimated individual external radiation doses using two types of information collected during the 4 months after the accident (March 11 to July 11, 2011). Information was gathered about residents' behaviors within their dwellings and other places that they visited, their modes of transportation, times of occupancy (indoor, outdoor), and the ambient dose equivalent monitored by the government and other related organizations (6).

On January 25, 2012, at their fifth reviewing board meeting, the Fukushima Prefectural Health Survey announced the provision of results for the individual external dose for 1,727 residents in the evacuation and deliberate evacuation areas to residents on December 13, 2011: 65 residents were from Iitate Village, 228 from Kawamata Town and 1,296 from Namie Town. Of these, 1,589 were not radiation workers (6). Among these 1,589 residents from the evacuation areas, 987 (62.8%) received <1 mSv; 1,335 (85.8%) received <2 mSv; 1,464 (93.9%) received <3 mSv; and 1,518 (97.4%) received <5 mSv. The maximum dose was 15 mSv (Fig. 2). The survey committee concluded from these radiation doses that health effects are unlikely to appear in the future (7, 8).

In February 2013, Fukushima Prefecture summarized the results of questionnaire responses from 477,121 out of 2,056,994 residents (23.3%) who resided in Fukushima Prefecture at the time of the accident. These results indicated that 256,281 (66.3%) of the residents had exposures <1 mSv, 367,175 (95.0%) had <2 mSv and 383,901 (99.3%) had <3 mSv (9) (Fig. 3).

MEASUREMENTS OF INDIVIDUAL EXTERNAL EXPOSURE USING A PERSONAL DOSIMETER

The measured individual external doses of Fukushima residents, obtained from personal dosimeter readings, are summarized in Table 2. The categories included the type of personal dosimeter and its sensitivity, measurement period, number and age of residents surveyed, and dose range. Each city reported a dose range by different summary methods.

Two types of personal dosimeters were used in each city: the Glass Badge® (Chiyoda Technol Corp.) was used in Fukushima City and Date City. While the Quixel Badge® (Nagase Landauer, LTD) was used in Nihonmatsu City, Tamura City and Koriyama City. The measurement principle behind the Glass Badge® is radio photoluminescence, while the Quixel Badge® uses optically stimulated

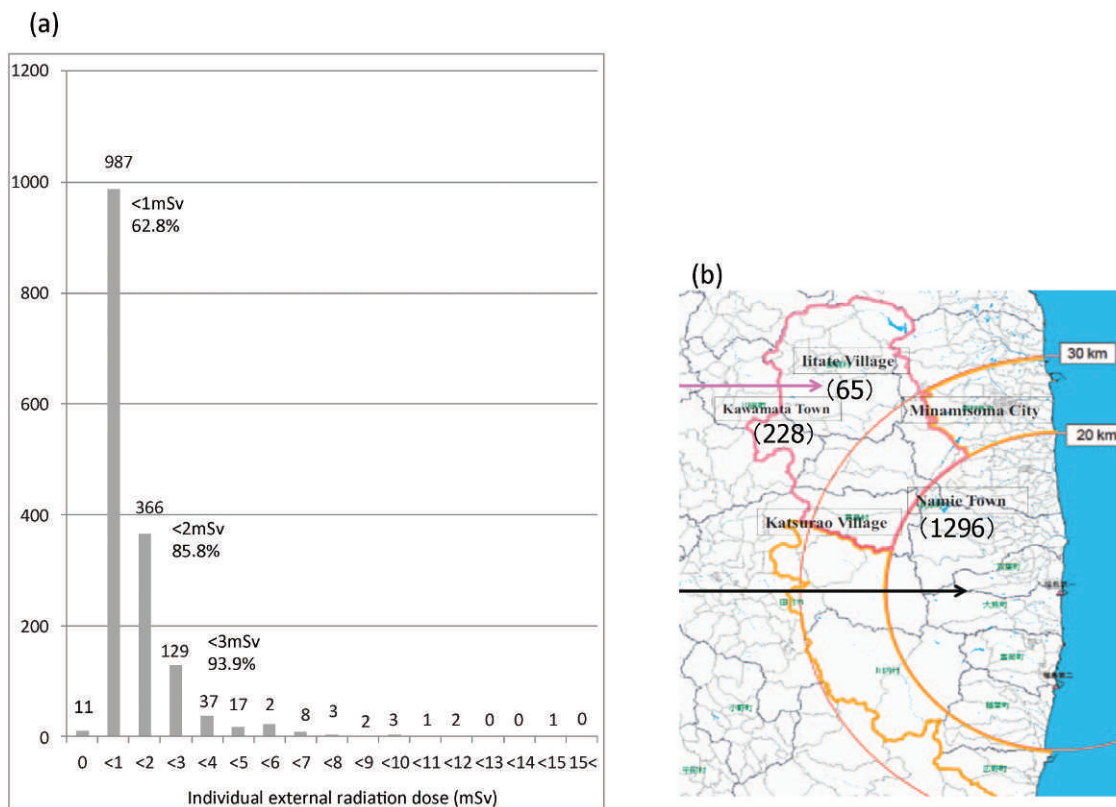


FIG. 2. Individual external radiation doses in the “evacuation” and “deliberate evacuation” areas during the first 4 months (panel a). The number of people examined in each village or town is indicated in panel b.

luminescence; the measurement limit of both types is 0.01 mSv.

In Fukushima City, personal dosimeters were distributed to infants, elementary and junior high school students and pregnant women. The measurement period was 3 months,

from September 1 to November 30, 2011. The individual accumulated external dose for a three-month period was obtained for 36,767 people. Fukushima reported the frequency distribution of accumulated doses in its residents as follows: 87.2% of surveyed residents received doses of

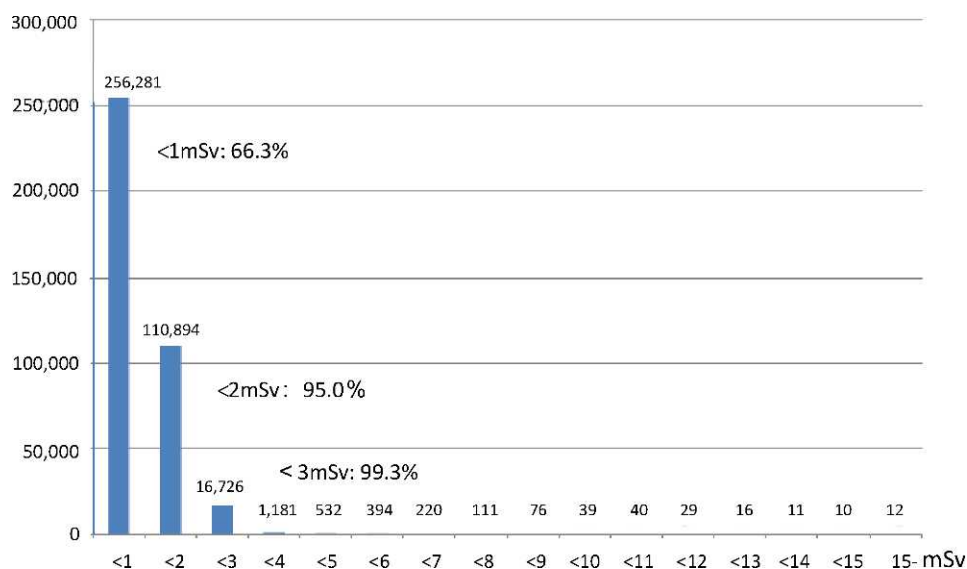


FIG. 3. Individual external radiation doses in Fukushima Prefecture. From a total of 2,056,994 subjects, 477,121 (23.2%) responded and 386,572 subjects who were nonradiation workers were analyzed.

TABLE 2
The Individual External Exposure Dose of the Residents in Fukushima Measured by Personal Dosimeters

City	Personal dosimeter		Measurement period	Number of residents surveyed	Age group	Dose range (frequency/districts/age group)
	Maker	Sensitivity				
Fukushima	Chiyoda Technol Corp. Glass Badge®	≥0.01 mSv	September 1 –November 30, 2011 (3 months)	36,767	Junior high school students and below, as well as pregnant women	Frequency distribution, accumulated dose (3 months) (D mSv) $D < 0.1$ mSv: 9.0% $0.1 \leq D < 0.5$ mSv: 78.2% $0.5 \leq D < 1.0$ mSv: 12.5% $1.0 \leq D < 1.5$ mSv: 0.25% $1.5 \leq D < 2.0$ mSv: 0.027% $2.0 \leq D < 2.5$ mSv: 0.005% $2.5 \leq D < 3.0$ mSv: 0.014%
Date (10)	Chiyoda Technol Corp. Glass Badge®	≥0.01 mSv	September 1 –November 30, 2011 (3 months)	9,443	All ages	District, average accumulated dose (3 months) Ryozen district: 0.71 mSv Tsukidate district: 0.43 mSv Hobara district: 0.31 mSv Date district: 0.20 mSv Yanagawa district: 0.17 mSv 0.3% (33 persons), ≥ 10 mSv/year 2 persons, ≥ 20 mSv/year Age group, average accumulated dose (3 months) 0–6 years: 0.41 mSv Elementary school: 0.37 mSv
Nihonmatsu (11)	Nagase Landauer, LTD Quixel Badge®	≥0.01 mSv	September 1 –November 30, 2011 (3 months)	8,725	0–6 years: 2,096 Elementary School: 3,158 Junior high School: 1,654 High School: 703 19–40 years (female): 1,079 Other students: 35	Elementary school: 0.37 mSv Junior high school: 0.37 mSv High school: 0.41 mSv 19–40 years (female): 0.38 mSv Other students: 0.28 mSv
Tamura (12)	Nagase Landauer, LTD Quixel Badge®	≥0.01 mSv	September 30, 2011 –January 10, 2012 (103 days)	4,559	Junior high school and below, as well as pregnant women	District (persons), average accumulated dose (103 days) Takine (626): 0.10 mSv Ohgoe (509): 0.10 mSv Miyakoji (302): 0.17 mSv Tokiwa (734): 0.16 mSv Funehiki (2,468): 0.15 mSv
Koriyama (13)	Nagase Landauer, LTD Quixel Badge®	≥0.01 mSv	November 7, 2011 –January 9, 2012 (64 days)	24,115	Elementary school / Junior high school	Frequency distribution, accumulated dose (64 days) Highest 1.31 mSv / Lowest 0.01 mSv / Average 0.17 mSv 0.01–0.09 mSv: 21.7% 0.10–0.19 mSv: 41.7% 0.20–0.29 mSv: 28.4% 0.30–0.39 mSv: 6.5% 0.40–0.49 mSv: 1.2% 0.50– : 0.37%

<0.5 mSv/3 months and 99.7% received <1 mSv/3 months. Cases where values exceeded 2 mSv were determined to be results of inappropriate use of the badges (e.g., placed outdoors, left on bicycles or put through X-ray inspection during baggage checks at the airport).

Date City and Tamura City totaled the personal accumulated doses of their residents according to district. Date City's measurements were obtained over 3 months and

reported as accumulated doses for residents of each district. The dose was lowest in Yanagawa district (0.17 mSv) and highest in Ryozen district (0.71 mSv) (10). Nihonmatsu City reported the accumulated doses over 3 months by age groups (i.e., elementary school students, junior high school students, etc.), with a dose range of 0.28–0.41 mSv (11). Tamura City measured the personal accumulated doses for 103 days, with a dose range from 0.10 mSv at Ohgoe and

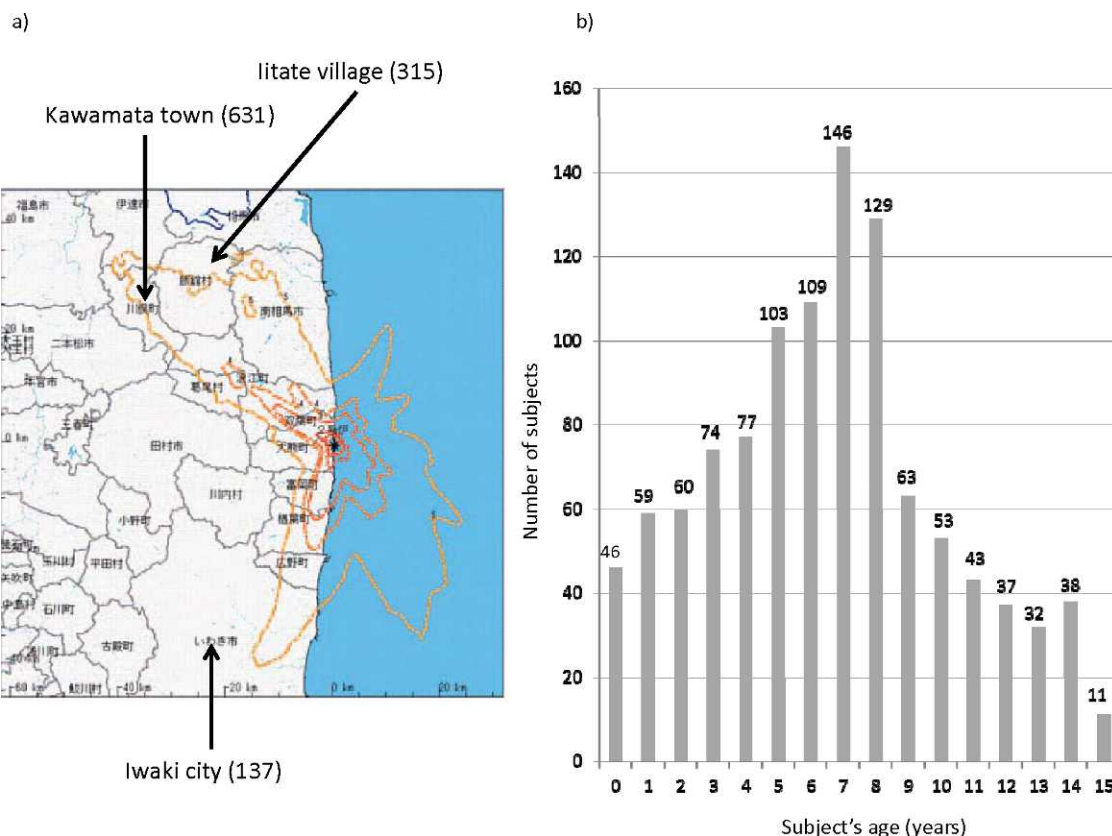


FIG. 4. Screening survey on thyroid exposure for children performed from March 26–30, 2011, by the Nuclear Emergency Response Headquarter and NIRS, indicated with the thyroid equivalent dose evaluated by SPEEDI system. The thyroid dose was calculated using the internal dose coefficients currently available from International Commission on Radiological Protection (ICRP) publication 72 and the age-dependent thyroid mass. We used a systemic model for iodine (ICRP publication 56) and general models of the respiratory tract for inhalation (ICRP publication 66). The dose estimation was also based on a scenario of chronic intake via inhalation from March 12, 2011, to the day before the measurement day. Panel a: the numbers in the parentheses indicates the number of people examined in each village or town and the age distribution of children is shown in panel b.

Takine to 0.17 mSv at Miyakoji (12). Koriyama City reported a frequency distribution for its residents with accumulated doses for 64 days; 91.89% of those surveyed had a dose range of 0.01–0.29 mSv (13).

Fukushima Prefecture announced the results of measurements made using personal dosimeters in its 22 municipalities, omitting the names of cities, towns or villages for reasons of personal information protection (14). The prefecture indicated that the median reported values were <1 mSv/year.

RADIATION DOSE TO THYROID GLANDS IN CHILDREN

The SPEEDI system suggested that the thyroid equivalent dose might have reached 100 mSv in hypothetical one-year-old children in some areas, based on the assumption of a continuous intake of contaminated foods from March 12–24, 2011. Thus, evaluation of the thyroid dose was urgent for residents in these areas.

The unavailability of thyroid monitors meant that an alternative thyroid monitoring method, using a NaI (TI)

scintillation survey meter, was used for ambient dose rate measurements. This test was performed from March 26–30, 2011.

Overall, 315 children ranging from 0–15 years of age from Iitate Village, 631 from Kawamata Town, and 137 from Iwaki City participated in the survey. The number of children are shown in Fig. 4a and the age distribution of these children is shown in Fig. 4b. Figure 5 shows the distribution of thyroid equivalent doses estimated from the screening survey and intake scenario from March 12, 2011, to the day before measurement: 95.7% of the children received <10 mSv, with a maximum of 35 mSv, which is lower than the intervention level (50 mSv) (15, 16). In Fig. 6, these values are compared to those of the dose-response relationship between thyroid cancer and iodine-131 (^{131}I) in the Ukraine and Belarus as a result of the Chernobyl accident (17, 18). Values for Fukushima are shown on the red line in the figures.

In a separate project, Tokonami *et al.* conducted ^{131}I -activity measurements of the thyroid glands of 62 residents and evacuees during the period from April 12–16, 2011, by placing a NaI (TI) scintillation spectrometer

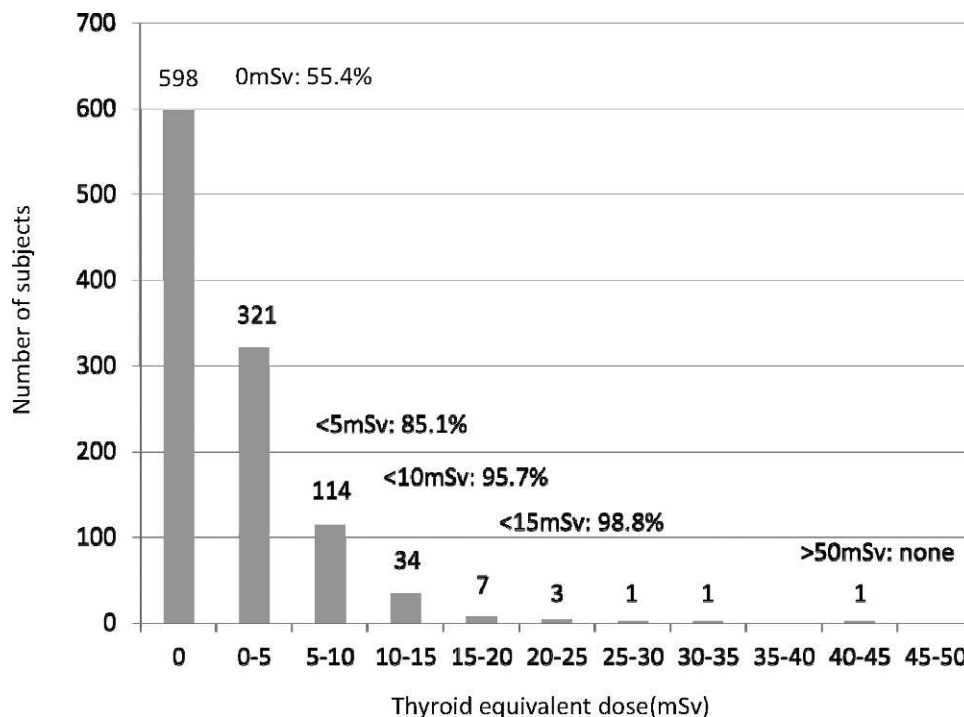


FIG. 5. Distribution of thyroid equivalent doses estimated by the results of the screening survey and the intake scenario from March 12, 2011 to the day before measurements.

on the neck of examinees. They found detectable ^{131}I activity in 39 of the 45 people evacuated from coastal areas, and in 7 of the 17 residents in Tsushima District (Nami Town). Thyroid equivalent doses by inhalation ranged from none detected to 33 mSv (19). The median thyroid equivalent doses for children and adults were 4.2 and 3.5 mSv, respectively.

Internal Doses Evaluated by WBC

Internal contamination with radionuclides in the whole body was also a concern for residents in Fukushima Prefecture; therefore, the Fukushima prefectural government monitored internal radionuclide contamination in residents. A preliminary study of 174 residents was

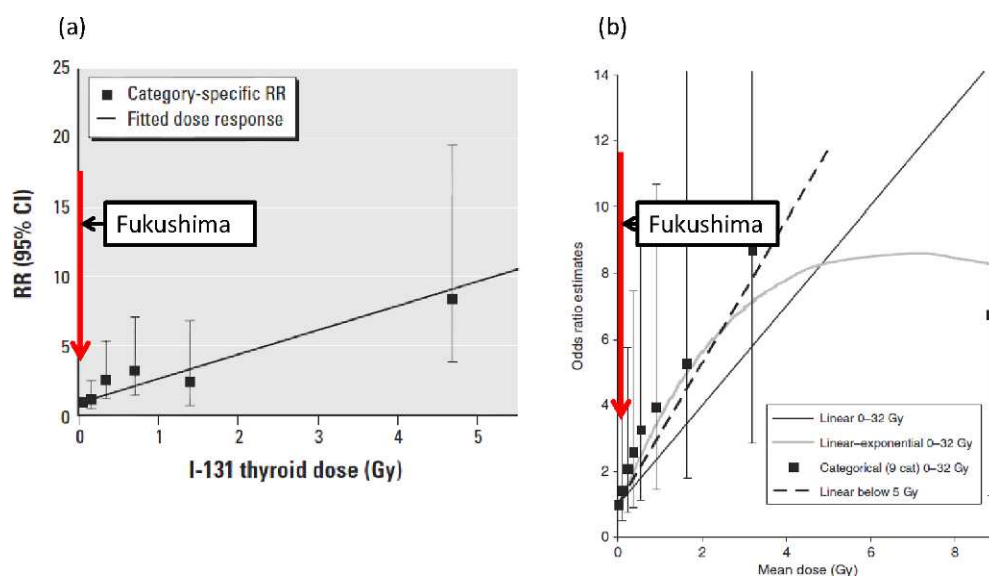


FIG. 6. Panel a: Thyroid radiation doses in Fukushima, Ukraine and Belarus in dose-response relationship between thyroid cancer and ^{131}I . Panel b: Dose-response relationship for the incidence of thyroid cancers. Both figures were modified from two articles (republished with permission, Brenner AV, et al. *Environ Health Perspect* 2011;119:933-9 and Zablotska LB, et al. *Br J Cancer* 2011;104:181-7).

TABLE 3

Whole-Body Dose of Residents in Fukushima Prefecture

Dose	Number of residents
<1 mSv	118,904
1 mSv	14
2 mSv	10
3 mSv	2
Total	118,930

Notes. Whole-body doses were calculated based on the assumption that ^{134}Cs and ^{137}Cs were inhaled on March 12, 2011, for residents measured at the end of January 2012, or ingested continuously from March 12, 2011, for those measured afterward. This assumption was made so as not to underestimate the doses of residents. The results contain no serial measurement in the same person. The results are as of February 2013 and are available on the Fukushima Prefecture website (19).

performed at the NIRS in Chiba. The internal doses calculated were <1 mSv in all residents.

Fukushima Prefecture subsequently announced the results of internal radiation doses measured from June 2011 to February 2013. The total number of subjects, consisting of Fukushima Prefecture residents and evacuees in Niigata Prefecture was 118,930. Of these, 118,904 (99.9%) showed values of a committed effective dose (a measure of health effects on an individual due to an intake of radioactive material into their body) that was <1 mSv and the maximum was 3 mSv in two people (20) (Table 3).

The Minamisoma City office also monitored the internal doses of students at 579 primary/junior high schools, 4,745 high schools and in adults by whole-body counter (WBC) at the Minamisoma City General Hospital from September 26 to December 27, 2011 (21). The office reported the results on their website. This study was performed independently of other organizations, and one adult had 1.1 mSv as a committed effective dose, while the doses of the students and other adults were <1 mSv.

Tsubokura *et al.* evaluated the ^{137}Cs body burdens of 1,432 children and 8,066 adults by WBC in Minamisoma City, 23 km from the Fukushima Daiichi Nuclear Power Plant, and reported low-exposure levels in most adults and children tested (22). Values were much lower than those reported in studies years after the Chernobyl accident (49 Bq/kg after 7–10 years). Hayaho *et al.* also carried out a WBC survey in 32,811 people between October 2011 and November 2012, and showed that the ^{137}Cs body burdens of all children ($n = 1,383$) were below the detection limit of 300 Bq/body in the fall of 2012 (23).

At Nagasaki University, Nagasaki Prefecture, Matsuda *et al.* measured internal radioactivity by WBC in evacuees and short-term visitors to Fukushima within one month after the accident, and reported that ^{131}I , ^{134}Cs and ^{137}Cs were detected in more than 30% of examined individuals, at maximum committed doses and thyroid equivalent doses of 1 and 20 mSv, respectively (24).

DISCUSSION

The World Health Organization (WHO) recently assessed public health risks due to the Fukushima Daiichi Nuclear Power Plant accident and reported that the two most affected locations of Fukushima Prefecture showed preliminary estimated radiation effective doses for the first year ranging from 12–25 mSv (25). The WHO also estimated that the lifetime risks are predicted to increase to around 7% for leukemia in males exposed as infants; for thyroid cancer, the estimated lifetime risk increases to around 70% in females exposed as infants. However, these estimates are based on the assumption that people in the most affected areas outside the 20-km radius continued to live there for four months after the accident (26).

Countermeasures at the outset of the accident were carried out according to the radiation dose calculated from the readings at the monitoring posts. These countermeasures considered several assumptions from the point of view of protection and safety. Evacuation was planned to avoid an external exposure of >20 mSv/year and food was strictly controlled to limit internal exposure. In this article, we reviewed the screening results of thyroid equivalent doses in the initial phase of the accident in Iitate Village, Kawamata Town and Iwaki City, and showed that 95.7% of the children received <10 mSv, with a maximum of 35 mSv, which is lower than the intervention level (50 mSv) (15, 16). Thyroid equivalent doses around Chernobyl have been extensively estimated. Zablotska *et al.* estimated individual thyroid doses in Belarus based on individual thyroid activity measurements and dosimetric data from questionnaires (18). They estimated that thyroid doses ranged from nearly 0–32.8 Gy, with an arithmetic mean of 0.56 Gy, which were much higher than those in Fukushima. This suggests that compared to Chernobyl, the countermeasures at the outset of the accident in Fukushima effectively minimized the internal radiation exposure to the thyroid gland.

Information about individual radiation doses is now accumulating, and the exploratory committee of the Fukushima Health Management Survey has indicated on its web site (9) that radiation from the accident will not likely be the cause of health effects in the future. Based on several assumptions, the individual radiation doses experienced by residents during the first 4 months of the accident are very different from those estimated by the readings of the monitoring posts. A clear difference between the ambient dose equivalent and the individual dose rate has been reported by Yoshida *et al.* (27).

In any event, sincere scientific efforts must be continued to obtain individual radiation doses that are as accurate as possible. However, the protocol for determining the health effects of radiation has to be reevaluated to observe the health effects due to individual radiation doses (e.g., external doses <5 mSv/first 4 months, internal doses <1 mSv/year and thyroid doses <35 mSv). Dose-responsiveness is crucial and collecting sufficient data to confirm the

presence or absence of radiation health effects should be the aim of the survey.

In particular, the schedule of decontamination should be reconsidered. The current decontamination map is based on the results of airborne monitoring, and the radiation dose is calculated from the readings at the monitoring posts taken during the initial period of the accident. The decontamination protocol should be reconsidered to account for the individual doses of people who desire to live in those areas.

All stakeholders must consider the relationship between the estimated health effects and the consequences of countermeasures such as evacuation, resettlement, food control, decontamination and health examinations. The goal of countermeasures is to minimize the suffering of exposed residents and to promote recovery from the overall damage of the nuclear accident, the earthquake, and the tsunami.

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