

# Thyroid Consequences of the Fukushima Nuclear Reactor Accident

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## Key Words

Thyroid · Radiation · Nuclear accident

## Abstract

**Background:** A special report, 'The Fukushima Accident', was delivered at the 35th Annual Meeting of the European Thyroid Association in Krakow on September 11, 2011, and this study is the follow-up of the special report. **Objectives:** To present a preliminary review of potential thyroid consequences of the 2011 Fukushima nuclear reactor accident. **Methods:** Numerous new data have been presented in Japanese, and most of them are available on the website from each research institute and/or from each municipality. The review was made using these data from the website. **Results:** When individual radiation doses were expressed as values in more than 99% of residents, radiation doses by behavior survey in evacuation and deliberate evacuation areas were less than 10 mSv in the first 4 months, and internal radiation doses measured by whole body counters were less than 1 mSv/year. Individual thyroid radiation doses were less than 50 mSv (intervention levels) even in evacuation areas. As for health consequences, no one died and no one suffered from acute effects. The thyroid ultrasound examination is in progress and following examination of almost 40,000 children,

35% of them have nodules and/or cysts but no cancers. **Conclusions:** Countermeasures against radiation must consider current individual measured values, although every effort must be taken to reconstruct radiation doses as precisely as possible. At present, the difference of thyroid radiation dose between Chernobyl and Fukushima appears to be due to the strict control of milk started within a week after the accident in Fukushima. Since the iodine-131 plume moved around in wide areas and for a long time, the method of thyroid protection must be reconsidered.

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## Introduction

A special report, 'The Fukushima Accident', was delivered at the 35th Annual Meeting of the European Thyroid Association in Krakow on September 11, 2011, and this study is the follow-up of the special report. In view of the enormous damage caused by the Fukushima accident, numerous reports on health consequences and on exposed radiation doses have been presented and published one by one. This study is a summary of the reports currently available from the website in Japanese. Precise scientific evaluation on each report was impossible be-

cause scientific information on the methodology was not available on the website. This summary might give a one-sided view of the author, trying to transfer and interpret the reports published on various websites. The final conclusions on the health effects and exposed radiation doses may have to wait for 20–25 years or more as in the case of the Chernobyl accident.

## **Outline of the Accident [1, 2]**

### *Earthquake*

The Great East Japan Earthquake occurred at 14:46 on March 11, 2011 and had a magnitude of 9.0, the largest in Japan's recorded history. The earthquake occurred in an area where the Pacific plate sinks beneath the North American plate and the seismic source was at latitude 38.1 north and longitude 142.9 east, at a depth of 24 km. The Tsunami occurred in a series of seven waves, resulting in the inundation of an area of 561 km<sup>2</sup>. Almost 20,000 people are reported dead or missing.

### *The Incidence and Development of the Accident at the Fukushima Nuclear Power Plants*

At 14:46, nuclear power plants (NPSs) under operation automatically shut down by earthquake. However, all six external power supply sources were lost by earthquake and this caused the emergency diesel power generators to start up. At 15:27 (41 min later) and 15:35, seawater pumps, emergency diesel generators and distribution boards were submerged because of the Tsunami strikes and all emergency diesel power generators stopped. All AC power supplies were lost.

Nuclear fuel in each core was not covered by water but was exposed, leading to a core melt. Parts of the melted fuel stayed at the bottom of the reactor pressure vessel (containing nuclear reactor coolant and reactor core) and a part broke the bottom.

A large amount of hydrogen was generated by chemical reaction between the zirconium of fuel cladding tubes and water vapor. In addition, the fuel cladding tubes were damaged and radioactive materials therein were discharged into the reactor pressure vessel and then to the primary containment vessel (PCV).

The inner pressure rose in the reactor pressure vessel and this water vapor leaked into the PCV. Then, PCV wet well vent operations were carried out a number of times, during which the gases in the PCV were released into the atmosphere.

## **Outline of Countermeasures at the Initial Phase [1, 2]**

### *Evacuation and Shielding*

At 20:50 on March 11, the Governor of Fukushima Prefecture instructed Okuma Town and Futaba Town to evacuate their residents and others within a 2-km radius of Fukushima Dai-ichi NPS.

At 21:23 on the same day the Director-General of the Nuclear Emergency Response Headquarters (Prime Minister) issued an instruction to the heads of Fukushima Prefecture, Okuma Town, Futaba Town, Tomioka Town and Namie Town. This instruction was to evacuate the residents and others within a 3-km radius of Fukushima Dai-ichi NPS and to order the residents and others within a 10-km radius of the NPS to stay indoors. Responding to the situation that the reactor Unit 1 had not been cooled, these evacuation instructions were provided as a precaution in case the situation should continue.

At 5:44 on March 12, the Director-General of the Nuclear Emergency Response Headquarters instructed residents within 10 km of the NPS, who were originally instructed to stay indoors, to evacuate to outside of the evacuation area. This instruction was issued because of the possibility that the pressure in the PCV was increasing.

At 18:25 on the same day, responding to an explosion at Unit 1 of Fukushima Dai-ichi NPS and the related emergency measures, the Director-General issued a new instruction which was to evacuate the residents within a 20-km radius. It was issued to prepare for any possible risks which would occur simultaneously at multiple reactors including the units other than Unit 1.

From March 12 onward, various incidents at multiple units occurred including explosions which appeared to have been caused by hydrogen at Units 1 and 3 on March 12 and 14, respectively, an explosion incident and smoke at Unit 2, and an explosion and a fire at Unit 4 on March 15.

At 11:00 on March 15, the Director-General issued a new instruction which was to order residents within a radius of between 20 and 30 km of Fukushima Dai-ichi NPS to 'stay indoors.'

### *Food Control*

Regarding food stuffs including agricultural products, because of the radioactivity detected from the surrounding environments of Fukushima Dai-ichi NPS after the NPS accident, the Ministry of Health, Labor and Welfare notified each prefecture on March 17, based on technical advice from the Nuclear Safety Commission (NSC) Ja-

pan, that 'guideline values for food and drink intake restrictions' provided by the NSC Japan should be provisional limit values for radioactive materials contained in food stuffs and that any food stuffs that contained radioactive materials exceeding these values should not be consumed. Values for iodine-131 are 200 Bq/kg for drinking water and milk, and 2,000 Bq/kg for vegetables. Values for radioactive cesium are 200 Bq/kg for water and milk, and 500 Bq/kg for the others.

The Ministry of Health, Labor and Welfare collected and disclosed the results of inspection findings transferred from local governments. In addition, in terms of items exceeding the provisional limit values, if their food-stuffs were thought to have covered wide areas, the Prime Minister (Director-General of the Nuclear Emergency Response Headquarters), issued instructions on March 21 to relevant governors of prefectures about distribution restrictions, based on advice from the NSC of Japan. As well as this, the Ministry of Agriculture, Forestry and Fisheries notified related parties on how to dispose of vegetables and raw milk (including distribution-restricted vegetables, etc.), from which radioactive materials were detected, based on technical advice from the Emergency Technical Advisory Body of the NSC on March 25, April 26 and May 6.

## Release of Radioactive Materials to the Environment

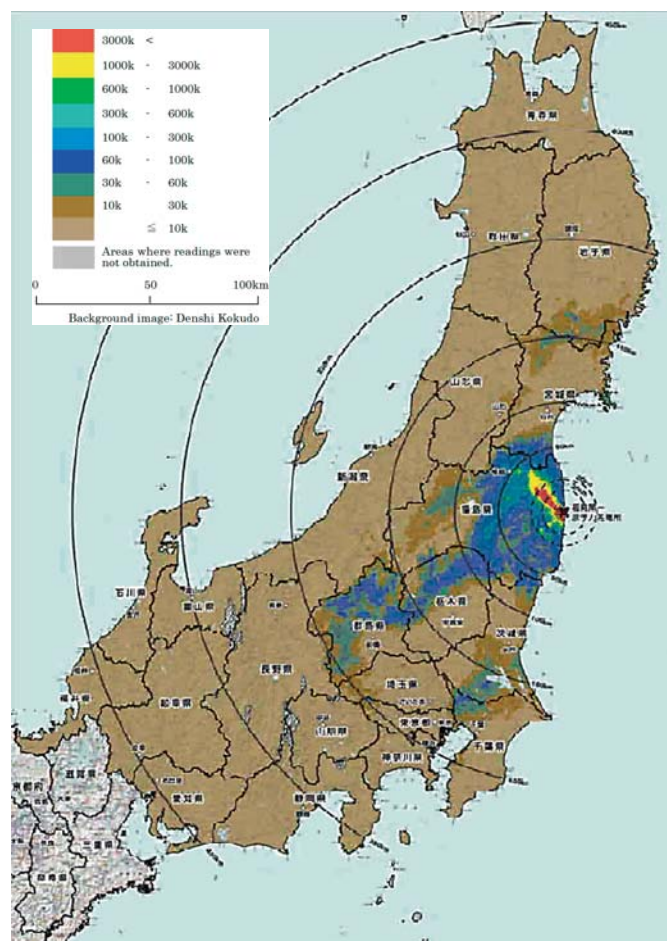
### Total Release of Radioactive Materials

Because of this accident, approximately  $1.8 \times 10^{16}$  Bq of cesium-134,  $1.5 \times 10^{16}$  Bq of cesium-137 and  $1.6 \times 10^{17}$  Bq of iodine-131 were released into the atmosphere [3]. Values are about one tenth of those at the accident of Chernobyl NPS.

Figure 1 shows the total deposition of cesium-134 and cesium-137 on the ground surface throughout all of East Japan, reflecting the results of the Fourth Airborne Monitoring Survey published on December 16, 2011 [4]. Values are expressed as kBq/m<sup>2</sup> as the same expression employed at the accident of the Chernobyl NPSs.

### Release of Radioactive Materials at the Initial Phase

Discharge occurred several times on March 12, 15 and 16th. The Plume of iodine-131, cesium-134 and cesium-137 moved around with the wind and fell down according to the weather and the configuration of the surface of the ground. Rain was one of the most important factors.



**Fig. 1.** The total deposition of cesium-134 and cesium-137 on the ground surface throughout all of East Japan expressed as kBq/m<sup>2</sup>. Results of the Fourth Airborne Monitoring Survey by MEXT (December 16, 2011) [4].

On March 14, the Fukushima Prefecture performed ambient dose monitoring, and the results appeared on the website every day. Figure 2 shows readings at the monitoring points in Fukushima Prefecture from March 11 to March 26, 2011. Most of the monitoring devices were damaged by the earthquake and the Tsunami, and the figures were made according to information on the website of MEXT [5].

The left panel of figure 3 shows the results of airborne monitoring by MEXT and DOE expressed as microsievert/hour on April 29th [6], and the right panel of figure 3 depicts the results from monitoring posts in April, also expressed as microsievert/hour [7].

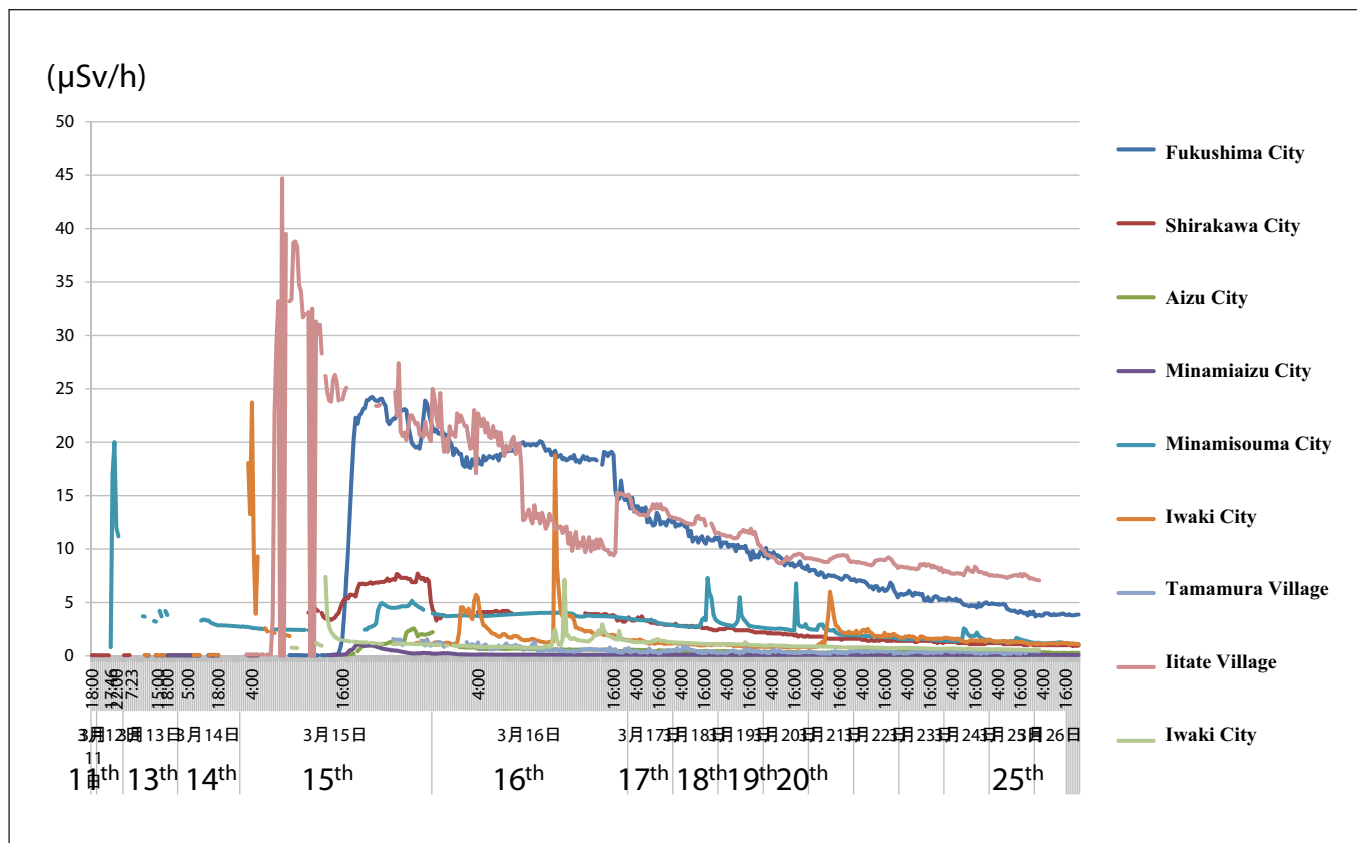


Fig. 2. Readings at the monitoring points in Fukushima Prefecture from March 11 to March 26, 2011 at 9 monitoring points [5].

### Establishment of 'Deliberate Evacuation Area'

On April 22, the Nuclear and Industrial Safety Agency informed that a 'Deliberate Evacuation Area' was established in accordance with the Act on Special Measures Concerning Nuclear Emergency Preparedness (fig. 4). As there was a threat that estimated doses had reached 20 mSv in 1 year since the occurrence of the accident, residents and others were requested to evacuate to other areas by roughly 1 month later [8, 9].

The sphere of the area is Iitate Village (whole sphere), part of Kawamata Town (Yamakiya district), Katsurao Village (whole sphere excluding the area within a 20-km radius), Namie Town (whole sphere excluding the area within a 20-km radius), and part of Minamisoma City (fig. 4). Due to these decisions, almost 110,000 people have been evacuated since the accident.

### Estimated Radiation Dose

#### *Estimation by Nuclear Emergency Response Headquarters*

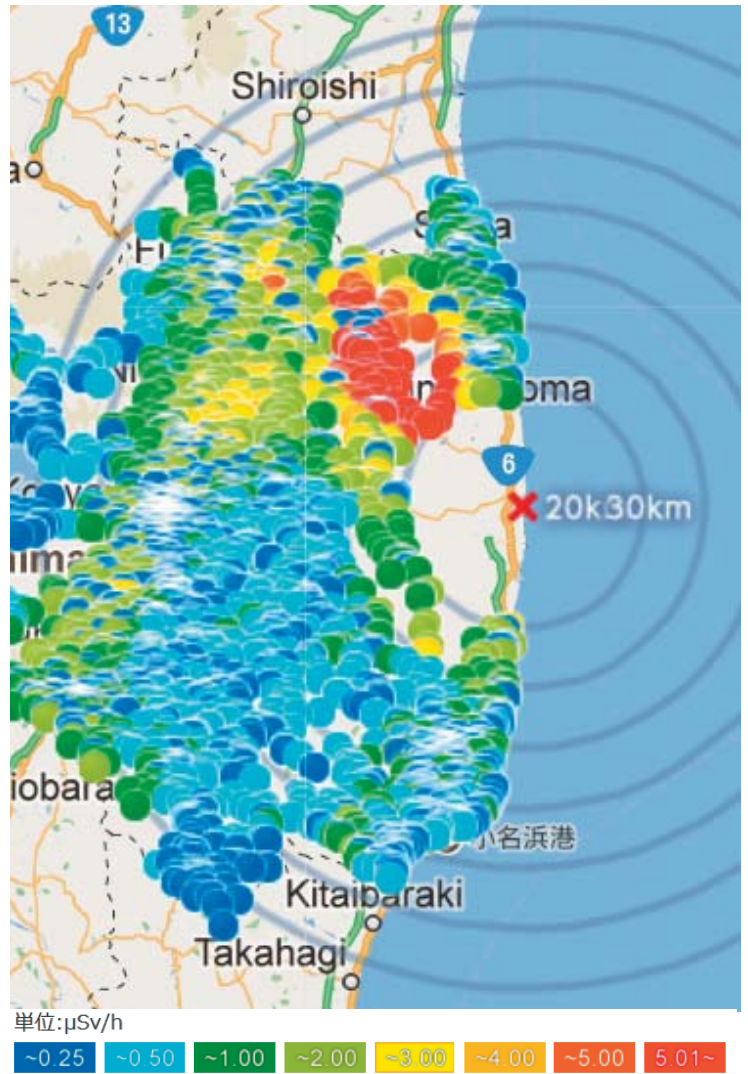
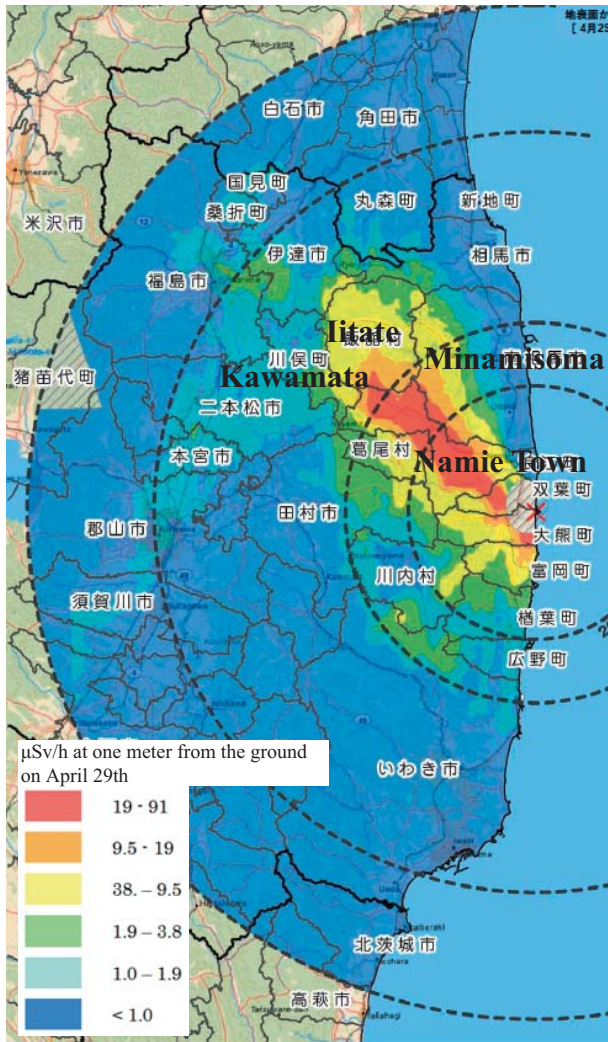
The headquarters employed 20 mSv as the reference level proposed by the International Commission on Radiological Protection from 20 to 100 mSv at the emergency exposure situation, and established 'Deliberate Evacuation Areas'. Therefore, the radiation exposure dose of the majority of residents was expected to be less than 20 mSv.

#### *Estimation by WHO*

WHO published 'Preliminary dose estimation from nuclear accident after the 2011 Great East Japan Earthquake and Tsunami' [10].

The assessment shows that the total effective dose received by characteristic individuals in two locations of relatively high exposure in Fukushima Prefecture as a result of their exposure during the first year after the acci-





**Fig. 3.** Left panel: the results of airborne monitoring by MEXT and DOE expressed as microsievert/hour at 1 m from the ground on April 29th [6]. Right panel: the results from monitoring points expressed as microsievert/hour in Fukushima Prefecture in April [7].

dent is within a dose band of 10–50 mSv. In these most affected locations, external exposure is the major contributor to the effective dose. In the rest of Fukushima Prefecture the effective dose was estimated to be within a dose band of 1–10 mSv.

The characteristic thyroid doses in the most exposed locations of Fukushima Prefecture were estimated to be within a dose band of 10–100 mSv. In one particular location the assessment indicated that the characteristic thyroid dose to 1-year-old infants would be within a dose band of between 100 and 200 mSv, with the inhalation pathway being the main contributor to the dose. Thyroid

doses in the rest of Japan were within a dose band of 1–10 mSv and in the rest of the world doses are estimated to be below 0.01 mSv and usually far below this level.

### Measurements of Individual Radiation Doses

#### *Estimation from a Behavior Survey*

The Fukushima Health Management Survey estimates the external exposure dose of residents based on their behavior. The National Institute of Radiological Sciences (NIRS) developed an ‘External radiation evaluating

system', which estimates individual external exposure doses during the first 4 months after the accident [11].

Using this system, the external exposure doses of 14,412 residents of Kawamata Town (704 residents), Namie Town (10,608) and Iitate Village (3,024) were estimated. In the results, 57.0% of the residents presented values of less than 1 mSv, 94.0% were less than 5 mSv and 99.3% had less than 10 mSv. The highest value was 25.1 mSv, found in 1 person who deliberately stayed in the evacuation area longer than the others. As mentioned before, Kawamata Town, Namie Town and Iitate Village belong to the evacuation and deliberate evacuation areas [12].

In addition, external radiation doses were obtained from 9,897 residents in other areas of Fukushima Prefecture. Although results were obtained from only 2% of residents in these areas, the maximum value was 3.9 mSv in the first 4 months; 94.2% were less than 2 mSv and 99.8% were less than 3 mSv [12].

#### *External Radiation by Personal Dosimeter*

In Fukushima City, glass badges were distributed to infants, students of elementary and junior-high schools and pregnant women from September 1 to November 30. The values averaged 0.2 mSv/3 months and were less than 1.0 mSv/3 months in 99.7% of the subjects. When expressed as microsievert/year, the values were less than 3 mSv in 97.7% of the subjects [13].

In addition, Fukushima Prefecture announced the results of personal dosimeter in 22 municipalities surrounding the evacuation and deliberate evacuation areas. The median value of residents in these 22 municipalities was less than 1 mSv/year [14].

Some of the cities announced the results on their own websites, and when doses were expressed as values in more than 95 or 99% of residents, they were less than 3.0 mSv/year in Date City [15], less than 3.0 mSv in Nihonmatsu City [16], and less than 1.2 mSv/year in Koriyama City [17] (fig. 6).

#### *Internal Radiation by Whole Body Counter*

Fukushima Prefecture announced the results of internal radiation dose measured from June 2011 to May 2012. The subjects included 45,694 residents in 12 municipalities of Fukushima Prefecture and evacuees in Niigata Prefecture. 45,668 (99.9%) of the residents showed that values for committed effective dose (a measure of health effect on an individual due to an intake of radioactive material into their body) were less than 1 mSv and the maximum value was 3 mSv in 2 persons [18].

#### *Thyroid Radiation Dose Determined by a NaI (TI) Scintillation Survey Meter*

As mentioned before, approximately  $1.8 \times 10^{16}$  Bq of cesium-134,  $1.5 \times 10^{16}$  Bq of cesium-137 and  $1.6 \times 10^{17}$  Bq of iodine-131 were released into the atmosphere. The System for the Prediction of Environmental Emergency Dose Information (SPEEDI) 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 from March 12 to March 24, 2011 (fig. 5) [19]. Thus, it was of urgent need to evaluate the thyroid dose for residents in these areas. However, the Director-General of the Nuclear Emergency Response Headquarters issued an instruction for evacuation from a 20-km radius and personnel of the local headquarters were also asked to evacuate immediately. Thyroid monitors were left within the evacuation areas and could not be used for the measurements.

Due to the unavailability of thyroid monitors, an alternative thyroid-monitoring method was suggested using a NaI (TI) scintillation survey meter which is used for ambient dose rate measurements.

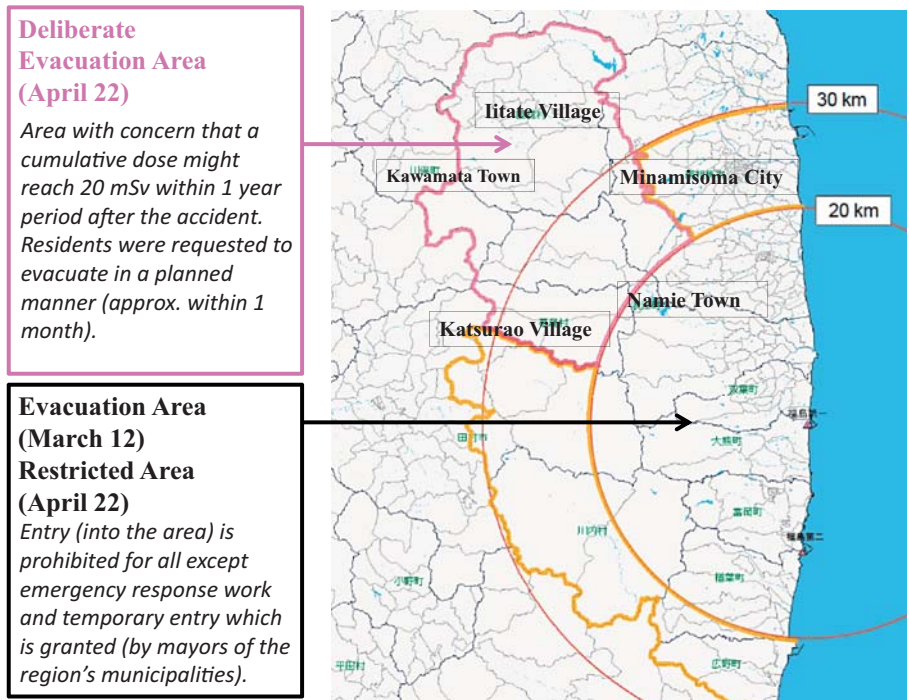
This test was performed from March 26 to March 30, 2011, using a NaI (TI) scintillation survey meter. The screening level was set under the assumption that a reading of 0.2  $\mu$ Sv/h on the survey meter corresponds to 100 mSv in the case of 1-year-old infants based on experiments by the NIRS.

Using this method, the radiation doses of 1,080 children under the age of 15 were measured in Iwaki City (134 children), Kawamata Town (647) and Iitate Village (299) in Fukushima Prefecture on the advice of the NSC. No children showed a level of 0.2  $\mu$ Sv/h or more, and the highest level was 0.1  $\mu$ Sv/h. Of these children, 55% showed background levels or lower, and 0.01  $\mu$ Sv/h was detected in 26%; 99% had levels less than 0.04  $\mu$ Sv/h [20, 21].

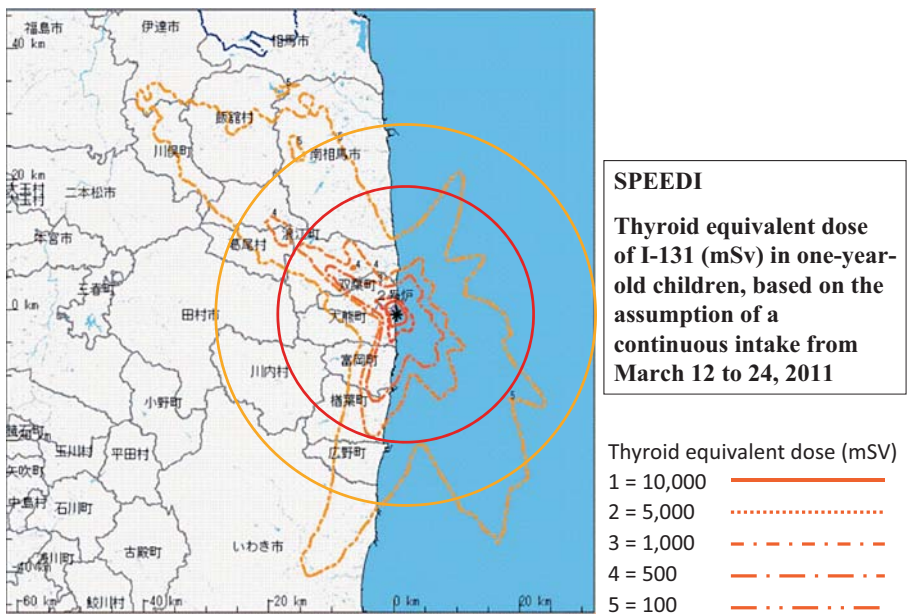
#### *Thyroid Radiation Dose Determined by a NaI (TI) Scintillation Spectrometer at the Neck of Examinees*

Thyroid radiation doses in evacuees from Fukushima were determined in Hirosaki City. The thyroid dose was determined by NaI (TI) scintillation spectrometer at the neck of the examinees. The median thyroid equivalent dose in 62 evacuees was estimated to be 4.2 mSv for children and 3.5 mSv for adults, and the maximum values were 23 and 33 mSv, respectively. Five children under the age of 9 and a total of 8 under the age of 20 were included. None of them showed values greater than the intervention level (100 mSv) [22].





**Fig. 4.** ‘Deliberate Evacuation Area’ and ‘Restricted Area’ (evacuation area on March 12) established on April 22 [8, 9]. The sphere of the area is Iitate Village (whole sphere), part of Kawamata Town, (Yamakiya district), Katsurao Village (whole sphere excluding the area within a 20-km radius), Namie Town (whole sphere excluding the area within a 20-km radius) and part of Minamisoma City.

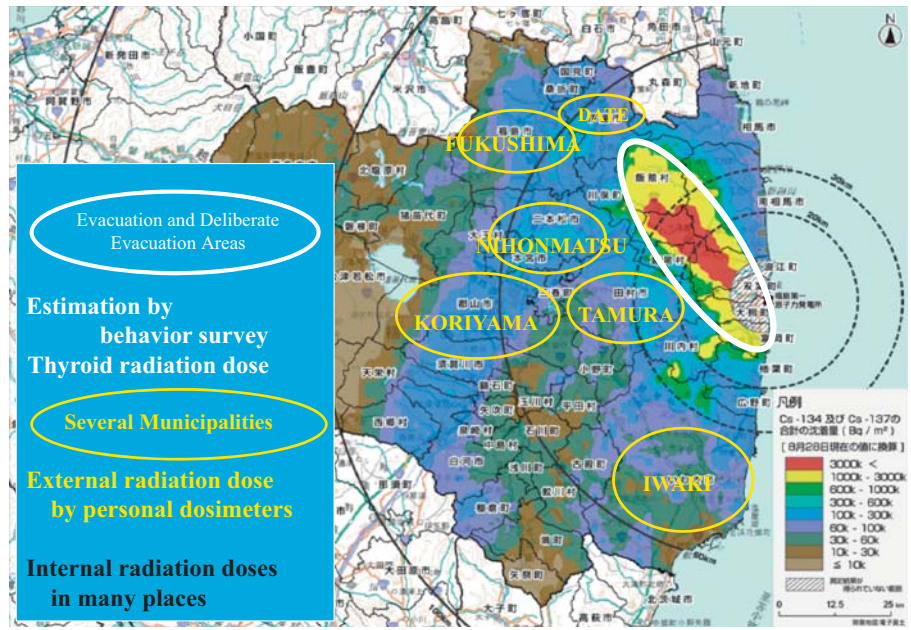


**Fig. 5.** Results of the SPEEDI. The SPEEDI suggested that the thyroid equivalent dose might reach 100 mSv in hypothetical 1-year-old children in areas even outside of the evacuation area [19].

*Thyroid Radiation Dose of Short-Term Visitors to Fukushima within 1 Month after the Accident*

In Nagasaki University, internal radioactivity was monitored by the horizontal bed-type scanning whole body counter for 173 people who stayed for 4.8 days on

average in Fukushima from March 11 to April 10, 2011. Subjects in the earlier days comprised of evacuees from Fukushima Hama-dori (east side of Fukushima Prefecture) including residents and visitors. Multiple intakes of iodine-131, cesium-134 and cesium-137 were found in 20



**Fig. 6.** Areas where measurements of individual radiation doses were performed.

of these 45 subjects. The highest committed effective dose as a sum of iodine-131, cesium-134 and cesium-137 was 1 mSv which was mainly contributed by iodine-131. The thyroid radiation dose of the same subject was 20 mSv which is under the intervention level [23].

### Health Consequences

#### *Acute Effects of Radiation*

It has to be noted that no one died by radiation and there are no patients with acute radiation syndrome from the accident at Fukushima NPSs. Two workers within the nuclear plant were suspected to be suffering from beta burns, but diagnosis was not confirmed by examination in the hospital of the NIRS.

#### *Late Effects of Radiation*

**Plant Workers.** Based on a review of the International Commission on Radiological Protection recommendations (publication 60) by MEXT's Radiation Review Council, the effective emergency dose for radiation workers was revised upward from 100 to 250 mSv. Although acute radiation syndrome was not found in plant workers, some of them received radiation of more than 100 mSv. Individual exposed radiation doses were registered, and health examination for late health effects will be per-

formed according to the regulation with regard to plant workers.

**Residents.** Maximum exposure among residents has not exceeded 20 mSv/year, and individual radiation doses determined by behavior survey were less than 10 mSv even in residents of the evacuation and deliberate evacuation areas. The results of individual internal radiation by whole body counter were less than 1 mSv anywhere in Fukushima Prefecture. The possibility of late effects such as cancer is extremely low according to the current knowledge of radiation. However, the Fukushima Health Management Survey is in progress, and the following are details of the thyroid disease survey.

#### *Thyroid Ultrasound Examination by the Fukushima Health Management Survey*

**Protocol.** The subjects of the thyroid ultrasound examination program are 0- to 18-year-old residents of Fukushima Prefecture on March 11th, 2011 (approx. 360,000 subjects) [24]. The first phase of the survey from October 2011 to March 2014 will be called 'previous research' when radiation-induced thyroid diseases do not appear, and the results will serve as control. After April 2014, the survey will be performed once every 2 years for residents under 20 years of age and once every 5 years thereafter for their entire lives.



**Table 1.** Categories of diagnosis at the thyroid ultrasonic examination of Fukushima Prefecture and the number of subjects in each category

	Total	0–5 years	6–10 years	11–15 years	≥16 years
A1	24,468 (64.2%)	8,526	6,391	6,100	3,415
A2	13,460 (35.3%)	1,367	4,254	5,300	2,539
B	186 (0.5%)	9	17	66	94
C	0 (0%)	0	0	0	0

A1 = Without nodules or cysts; A2 = with nodules (less than 5.0 mm) and/or cysts (less than 20.0 mm); B = with nodules (greater than 5.1 mm) and/or cysts (greater than 20.1 mm); to the next step of examination; C = to the next step of examination.

In the initial period of the first phase of the survey, subjects were mainly from evacuation areas and the results of the survey performed during 2011 were reported on the website of Fukushima Prefecture.

*Results Obtained in June, 2012.* Although the formal report in English will be published in the near future, the results obtained in 2011 were reported in Japanese on the website of Fukushima Prefecture. According to the website in June [12], the survey was performed on 38,114 children in 2011, and the results of ultrasound examination were divided into four categories (table 1).

The number of subjects in each category is also shown in table 1. Ninety nine percent of children belong to A1 and A2, but it is to be noted that 35% of the subjects belong to A2 with nodules (less than 5.0 mm) and/or cysts (less than 20.0 mm) and 14% of children from 0 to 5 years of age are A2.

When frequencies of nodules and cysts are expressed as a percentage of the subjects, 1% had nodules and 0.5% had nodules greater than 5.1 mm. With regard to cysts, 35% had cysts and all of them were less than 20 mm.

As shown in table 1, many children were already found to have small cysts and/or nodules at the thyroid ultrasound examination by the Fukushima Health Management Survey. Examinations of almost 40,000 children were performed in the investigation of the Chernobyl accident, but it is impossible to say whether the current results of this initial phase are normal or abnormal at this time of the examination. However, the high frequency of cysts or small nodules in this examination is due to the much more improved instruments than those employed for the thyroid screening of the Chernobyl accident [25].

## Discussion

Following the outline of the accident and the countermeasures, the results of currently available measurements of individual radiation doses (mainly from the website in Japanese) are described.

In the areas of evacuation and deliberate evacuation where residents were evacuated within a few days, or before the accumulated radiation doses were estimated to reach 20 mSv/year, individual radiation effective doses were less than 10 mSv in the first 4 months in 99% of the residents.

Thyroid radiation doses of children in the evacuation areas were less than 0.04  $\mu$ Sv/h in 99% of cases and no one had levels higher than 0.2  $\mu$ Sv/h (corresponds to 100 mSv). In addition, thyroid radiation doses were determined in evacuees from Fukushima to Hirosaki City by NaI (TI) scintillation spectrometer at the neck of examinees. None of them showed values greater than the intervention level (100 mSv) [22]. Thyroid radiation doses of evacuees (residents and visitors) from Fukushima to Nagasaki were determined by whole body counter. The highest dose for thyroid was 20 mSv [23].

As shown in figure 4, SPEEDI estimated thyroid doses of 100–10,000 mSv, and the estimation by WHO is 10–100 mSv. There is no objection to these estimations on the safe side. However, it is important to realize that there exists a big gap between estimated values and measured values.

Since there are no patients with acute radiation syndrome, the major health consequences will be the late effects of radiation. The results of measurements of individual radiation doses are essential in considering the countermeasures against health consequences.

It should be noted, however, that these currently available results of individual measurements may be different from the final conclusions in the future. The following data may be obtained before the final conclusions:

(1) Results of the actual radiation doses of evacuees measured in the various institutes in other cities may be available in the near future.

(2) Results of the simulation of the movement of the iodine-131 plume using the results of several monitoring posts with spectrometers may soon be available. Results of deposition of iodine-131 on the ground, and the results of monitoring posts without spectrometer are not enough to show the movement of the iodine-131 plume. The results of simulation of the movements of the iodine-131 plume may show a possible uptake of iodine-131 from the plume in some areas. Simulation is now in

progress, and the results may appear in the near future (within 1 year).

(3) Information on the behavior of subjects who receive the thyroid ultrasound examination may become available. Information on behavior is essential when radiation doses are reconstructed by the movements of the iodine-131 plume, and by any additional data on environmental radiation.

Although there exist several possibilities to reconstruct thyroid radiation doses in the future, it is natural to accept the current results of the direct measurements of thyroid radiation doses which are lower than the intervention level (50–100 mSv) shown by three different institutes (NIRS, Hirosaki and Nagasaki University) and much lower than the thyroid radiation doses from the Chernobyl accident.

The big difference between the thyroid radiation doses in Fukushima and Chernobyl may be due to the strict control of the contamination of milk from March 17th. In other words, a high thyroid iodine-131 uptake in the Chernobyl accident is due to the contaminated milk as written in the Chernobyl Forum [26] as well as the report of UNSCEAR [27].

The low thyroid radiation dose in Fukushima may also be due to the instruction of the Director-General of the Nuclear Emergency Response Headquarters to evacuate the residents within a 20-km radius at 18:25 on March 12, and the instruction to order residents within a radius of between 20 and 30 km from Fukushima Dai-ichi NPS to stay indoors at 11:00 on March 15th.

The other difference is the dietary intake of iodide; the Ukraine, the Republic of Belarus, and the Russian Federation are iodine-deficient areas and Japan is an iodine-sufficient area [25].

Countermeasures against radiation must be based upon the radiation dose. The detailed survey of thyroid ultrasound examination in Fukushima Prefecture is a good example of how to discuss the significance of a health survey in relation to radiation doses, which can be different according to the results of the investigation (e.g. estimation compared to actual measurements).

If the thyroid radiation doses of all children surrounding Fukushima NPS are less than the intervention level as current direct measurements of individual thyroid radiation doses, the prefecture-wide thyroid examination of 360,000 children may not be justified on scientific standpoint.

The thyroid examination program started mainly by requests from psychological and social demands, and the most important and troublesome task is how to explain

the results of the examination to patients, families and to the public. Many children were already found to have small cysts and/or nodules, and most of them will have no clinical thyroid diseases in their lives. Thyroid radiation doses less than the intervention level were obtained from only 1,000 children; therefore, it is impossible to determine radiation-induced from nonradiation-induced thyroid cancer.

One of the possible ways to obtain additional data on radiation dose is to combine the movement of the iodine-131 plume and information of behavior. Information on behavior should be emphasized and should be obtained from all children at the time of thyroid examination.

Countermeasures against radiation following an accident of such enormous damage as this include evacuation, relocation, health examinations, compensation, etc. Accidents at NPSs are often accompanied by psychological and social problems, and countermeasures have to be considered not only from scientific but also from psychological, ethical, social and economic standpoints. In particular, communication must be guaranteed with residents who have hard feelings or grudges surrounding NPSs toward electric companies, the government, professionals and experts working for nuclear energy. Risk communication with residents is essential in this type of accident.

The most recent problem emerging from the accident at Fukushima NPS is how to protect thyroids by stable iodine when the radioactive plume is moving around in areas 50–60 km from the NPSs for more than 10–20 days.

In this accident, SPEEDI did not work well and it was uncertain whether stable iodine had to be administered or not [28, 29]. Finally, a few heads of municipalities ordered the administration of stable iodine, and iodine was given only once according to the instruction from the NSC.

As shown in figure 2, readings at the monitoring points were still elevated in areas 50 km from the NPSs at the end of March (at least for 20 days after the accident). It is clear that the plume moved around wide areas (at least 50 km from the NPSs) and for a long time (more than 3 weeks to a few months), and new methods for the protection of thyroids from radioactive iodine must be reconsidered. The questions are: how much, how often and how long stable iodine has to be administered. The difference of daily iodine intake in each country must also be considered.

The author would like to propose the necessity to establish new rules concerning the protection of thyroids from the plume following accidents at NPSs.

## Acknowledgement

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