# Atmospheric Dispersion Simulations for Estimating Radiation Dose to the Public
## –Reconstruction of Early Internal Dose to the Public in the TEPCO Fukushima Daiichi Nuclear Power Station Accident–

National Institute of Radiological Sciences, **Osamu Kurihara**

Given the limited availability of data from measurements conducted on affected people and the environment, atmospheric dispersion simulations played an essential role in estimating the early internal exposure doses for local residents affected by the accident that occurred at the Fukushima Daiichi Nuclear Power Plant (Station), which is operated by the Tokyo Electric Power Company. The estimates obtained from such simulations were also partially used in the previous fiscal year (2012), when the National Institute of Radiological Sciences reassessed the early internal exposure doses for residents of Fukushima Prefecture. This commentary describes the current status of, and future prospects for, internal exposure dose estimations produced by atmospheric dispersion simulations.

## I. Introduction

Radioactive nuclides were released into the environment due to the accident that occurred at the Fukushima Daiichi Nuclear Power Plant, which is operated by the Tokyo Electric Power Company (TEPCO). These nuclides were dispersed across an extensive area throughout eastern Japan and beyond. Their deposition on the ground surface exposed the public to radiation. To date, there have not been any reported cases of the public being exposed to excessive radiation; however, it is important to assess the exposure doses for individuals accurately to facilitate discussions on how human health will be affected by radiation in the future. The prefectural government of Fukushima has been conducting a health management survey for all residents of the prefecture [1). The basic data incorporates estimated external exposure doses for individuals. These estimates are conducted by combining the time-series data for the places where each individual resided based on their activity records using a two-dimensional map developed based on air dose rate data obtained from actual measurements performed in different parts of Fukushima in the immediate aftermath of the accident. As an exception, for a period beginning from the day after the accident (March 12 to March 14, 2011), the estimate made use of values calculated using the System for Prediction of Environmental Emergency

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Dose Information (SPEEDI). The necessary set of calculations is conducted by using an external exposure dose assessment system [2] developed by the National Institute of Radiological Sciences (NIRS). To date, the NIRS has estimated the external exposure doses for over 400,000 residents of Fukushima Prefecture by using this system in collaboration with Fukushima Medical University [3].

Meanwhile, the internal exposure doses of individuals have been estimated based on measurements conducted in Fukushima and other parts of Japan by using whole body counters. Almost all of the more than 100,000 Fukushima residents who have already been tested had a dose of less than 1 mSv [4]. It should be noted that each estimated internal exposure dose was the committed effective dose associated with the body intake of radioactive cesium. Due to a lack of sufficient data from measurements conducted on people and the environment, detailed estimates have not been made for the internal exposure doses associated with radioactive iodine and other nuclides with a short half-life that were present in the immediate aftermath of the accident. In the case of the Fukushima Accident, it would probably be difficult to apply the method for reassessing the doses received by local residents affected by the Chernobyl Accident; i.e., the method for associating the amount of nuclides deposited on the ground surface with individual internal exposure doses [5]. The reasons why this would be difficult include the considerable fluctuations in the ratio of iodine to cesium deposited on the ground surface as well as the earlier outward evacuation of residents living within 20 km of the Fukushima Daiichi Nuclear Power Plant. Given these circumstances, an atmospheric dispersion simulation is considered the only remaining option for complementing the dose estimations with data from actual measurements. The exploration of this possibility is vital for reassessing the doses received by the public.

In the previous fiscal year (2012), the NIRS attempted to reassess the early internal exposure doses for residents of Fukushima Prefecture—with a particular focus on thyroid equivalent doses (hereinafter referred to as "thyroid doses")—by combining the limited actual measurement data with atmospheric dispersion simulations [6]. The results are presented in **Table 1**. Partial reference was made to estimates from the atmospheric dispersion simulations. This commentary explains the background to this and describes the current status of, and future prospects for, early internal exposure dose estimations produced by atmospheric dispersion

**Table 1** Estimated thyroid doses for residents of Fukushima Prefecture (90th percentile)

| Municipality | Children aged one year | Adults | Reference data for dose estimate |
|---|---|---|---|
| Futaba-machi | 30 | 10 | Whole body counts |
| Okuma-machi | 20 | < 10 | Whole body counts |
| Tomioka-machi | 10 | < 10 | Whole body counts |
| Naraha-machi | 10 | < 10 | Whole body counts |
| Hirono-machi | 20 | < 10 | Whole body counts |
| Namie-machi | 20 | < 10 | Whole body counts and thyroid measurements* |
| Iitate-mura | 30 | 20 | Thyroid measurements and whole body counts |
| Kawamata-machi | 10 | < 10 | Thyroid measurements and whole body counts |
| Kawauchi-mura | < 10 | < 10 | Whole body counts |
| Katsurao-mura | 20 | < 10 | Substitution with data obtained in Namie-machi |
| Iwaki-shi | 30 | 10 | Atmospheric dispersion simulations and thyroid measurements |
| Minamisoma-shi | 20 | < 10 | Substitution with data obtained in Namie-machi |
| Other | < 10 | < 10 | Atmospheric dispersion simulations |

*Tokonami et al.[16] (Unit: mSv)

simulations.

# II. Calculation Method

Each internal exposure dose resulting from inhalation is calculated using the equation below by means of an atmospheric concentration map for a target nuclide obtained through an atmospheric dispersion simulation.

$$D_i = e_i \int C_i(x(t),t) \cdot B(t) \cdot F(t)dt$$

In this equation, the index $i$ denotes a nuclide, $D_i$ denotes the internal exposure dose from nuclide $i$, $e_i$ denotes the dose coefficient for internal exposure from inhalation, $C_i(x(t),t)$ denotes the atmospheric concentration at location $x(t)$ for the target individual at time t, $B(t)$ denotes the respiratory rate, and $F(t)$ denotes the correction factor for factors such as the dose reduction resulting from remaining indoors.

In the previous fiscal year, the NIRS reassessed the early internal exposure doses for residents of Fukushima Prefecture by adopting atmospheric concentration maps for $^{131}$I and $^{137}$Cs that were calculated using the second worldwide version of SPEEDI (WSPEEDI-II) [7]. These maps were available as two-dimensional time-series data (mapped only with the atmospheric concentration in the bottommost layer including the ground surface) for the period from March 12 to April 30, 2011, based on calculations covering all of eastern Japan (i.e., an area extending 690 km east-west and 960 km north-south). These maps had a horizontal spatial resolution of roughly 3 km each and a temporal resolution of one hour. Examples of WSPEEDI-II being applied to the Fukushima Daiichi Nuclear Accident are presented in some of the reference materials [8-10].

The abovementioned internal exposure dose coefficient and the respiratory rate were assigned with reference to values set in sources such as publications by the International Commission on Radiological Protection (for children aged three months, one year, five years, ten years, and 15 years as well as adults) [11, 12]. Although a reference was available for the dose reduction resulting from remaining indoors [13], this value was not taken into account in the present calculation.

The following section mainly presents the calculated thyroid doses resulting from the inhalation of $^{131}$I.

# III. Results and Discussion

## 1. Thyroid Dose Maps

**Figure 1** presents thyroid dose maps for children aged one year and adults. These maps were produced by multiplying the mapped atmospheric concentration for $^{131}$I with the thyroid equivalent dose coefficient (inhalation) for each of the corresponding age groups and the daily respiratory rate and then performing a time integration. The thyroid doses were assessed for the period from March 12 to March 31, 2011. Even if this period is extended, the thyroid dose increase is little. The thyroid equivalent dose coefficient was a weighted average of 60% of the coefficient for elemental iodine and 40% of the coefficient for particulate iodine (type F).

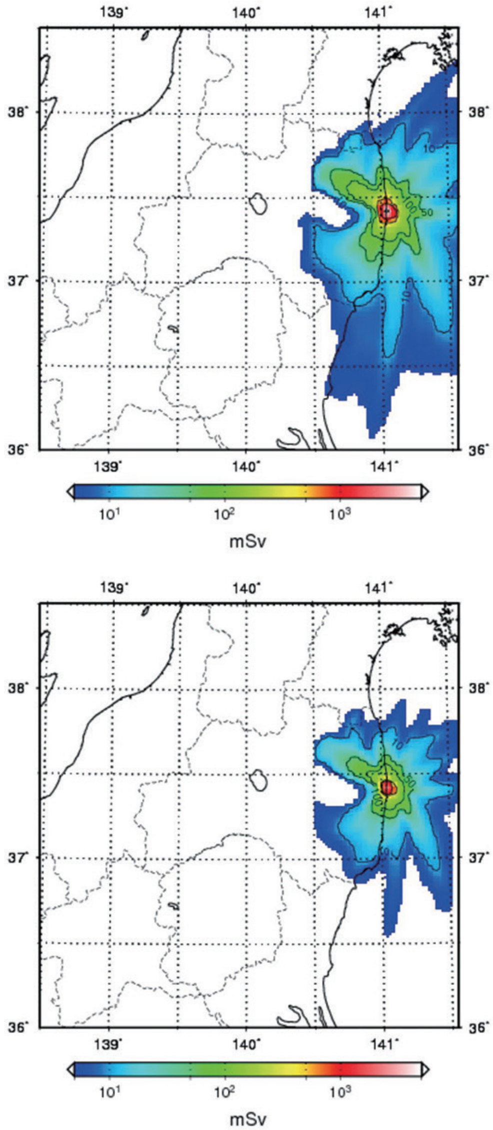


**Figure 1** Thyroid dose maps (top: children aged one year; bottom: adults)

The proportion of the physical properties of iodine was assigned with reference to the outcomes from air sampling performed on the premises of the Fukushima Daiichi Nuclear Power Plant, the Fukushima Daini Nuclear Power Plant, and the Japan Atomic Energy Agency in Ibaraki Prefecture.

The maps in Figure 1 show the thyroid doses for persons who remained outdoors at the relevant spots. These doses cannot be applied to residents who evacuated or otherwise moved from one place to another. In fact, most residents living within 20 km of the plant had already evacuated beyond this range by the end of March 12 [14]. These doses are likely to have been overestimated given factors such as the dose reduction resulting from staying indoors and the thyroid intake rate of iodine in blood among Japanese people [15]. For this reason, the thyroid dose maps in Figure 1 need to be interpreted with care. Nonetheless, they provide a general overview of the thyroid doses for local residents who did not move many times and residents in neighboring prefectures. In the map for children aged one year, the areas with a thyroid dose that far exceeds 10 mSv extend across the Hamadori region and its surrounding areas in Fukushima Prefecture.

## 2. Estimation of Thyroid Doses among Evacuees

Thyroid doses resulting from the inhalation of $^{131}$I among evacuees from the 20 km range or deliberate evacuation areas were estimated based on the model evacuation behavior cases (**Figures 2** and **3**) [2] that were referenced during estimations of the external exposure doses. These model cases were considered typical behavior patterns based on the actual routes taken by the evacuees. **Table 2** presents the thyroid doses from the respective model cases for children aged one year and 10 years as well as adults. The figures were rounded to one significant digit taking into consideration the required level of accuracy.

The doses in model cases for evacuations from the 20 km range are generally kept lower compared to those for evacuations from deliberate evacuation areas. This difference owes significantly to evacuations to beyond this range that took place before March 15 when a massive release occurred at the Fukushima Daiichi Nuclear Power Plant. Increased doses have been noted among evacuees who fled to the northwest of the plant. In model cases for evacuations from deliberate evacuation areas, almost all of the doses were received at the evacuees' points of origin because of the lateness of the evacuations.

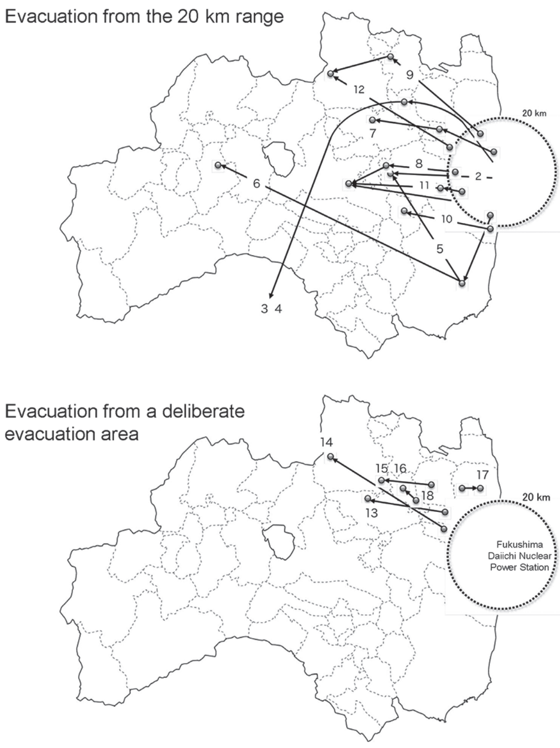


**Figure 2** Model evacuation behavior cases (top: evacuation from the 20 km range; bottom: evacuation from deliberate evacuation areas)

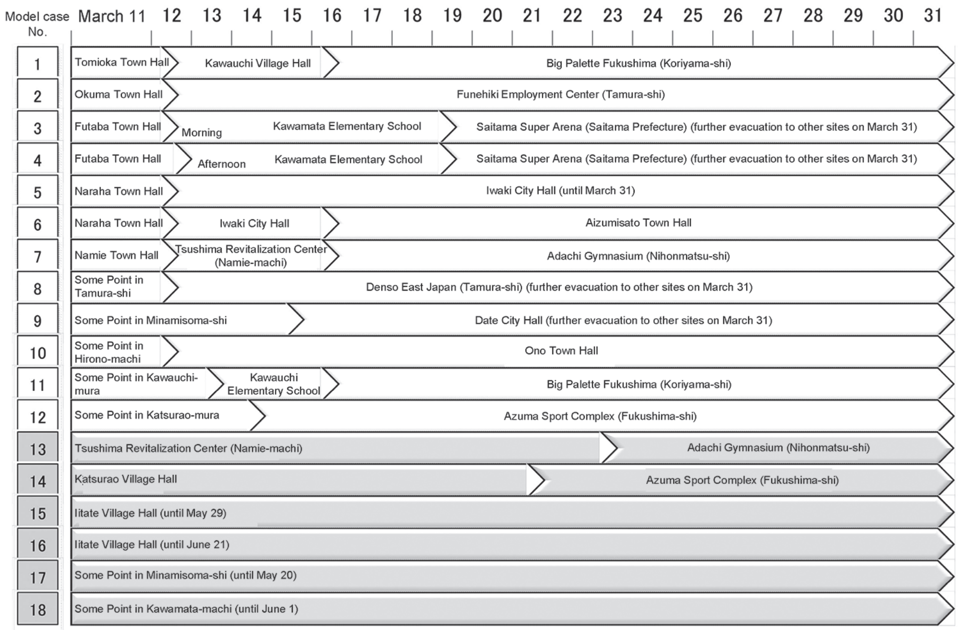


**Figure 3** Timeline for model evacuation cases (Cases 1–12: evacuation from the 20-km range; Cases 13–18: evacuation from deliberate evacuation areas)

**Table 2** Estimated thyroid doses from the inhalation of $^{131}$I according to model evacuation behavior cases by age group

| Model case No. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| Children aged one year | < 10 | < 10 | 40 | 90 | 30 | 10 | 90 | < 10 | < 10 |
| Children aged ten years | < 10 | < 10 | 40 | 70 | 30 | < 10 | 80 | < 10 | < 10 |
| Adults | < 10 | < 10 | 20 | 40 | 20 | < 10 | 50 | < 10 | < 10 |
| **Model case No.** | **10** | **11** | **12** | **13** | **14** | **15** | **16** | **17** | **18** |
| Children aged one year | 10 | < 10 | < 10 | 100 | 40 | 30 | 30 | 80 | 70 |
| Children aged ten years | < 10 | < 10 | < 10 | 90 | 30 | 30 | 30 | 70 | 60 |
| Adults | < 10 | < 10 | < 10 | 50 | 20 | 20 | 20 | 40 | 30 |

(Unit: mSv)

## 3. Comparison with Dose Estimations Based on Data from Actual Measurements Conducted on People

As means of verifying the accuracy of dose estimations produced by atmospheric dispersion simulations, a comparison with thyroid doses estimated based on limited data from actual measurements conducted on people (thyroid measurements and whole body counts) was attempted. The latter estimates, which are based on actual measurements, are probably closer to the true values despite a certain level of uncertainty associated with intake scenarios as conditions for calculating the internal exposure doses (e.g., intake dates and channels).

**Figure 4** shows the distribution of thyroid doses estimated based on the results of screening tests conducted in Kawamata-machi, Iwaki-shi, and Iitate-mura in late March 2011 to determine thyroid exposure among children. As an intake scenario, the inhalation of the entire amount of $^{131}$I on March 15 was assumed. This figure also shows thyroid doses estimated from the atmospheric dispersion simulations for the purpose of comparison. Because the addresses and behavior of the examined individuals were unknown, the thyroid doses for children aged 5 years were calculated based on the geometric mean (GM) and the geometric standard deviation ($\sigma_g$) for the atmospheric concentration of $^{131}$I extracted at the closest grid point to each municipal office in the calculation area used for WSPEEDI-II and eight adjacent grid points. As this figure demonstrates, thyroid doses estimated through atmospheric

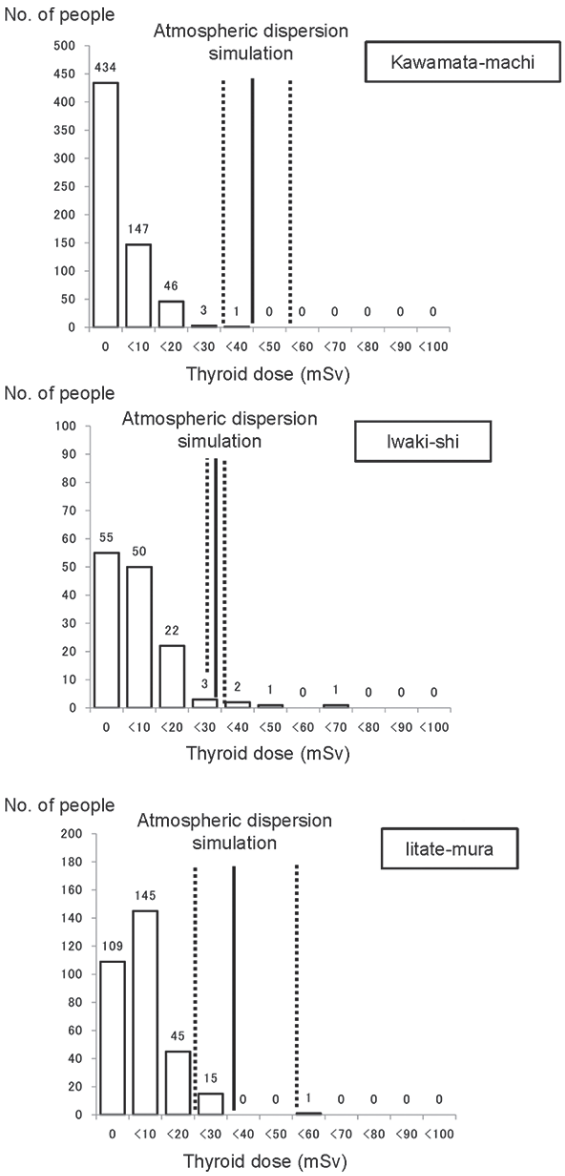


**Figure 4** Estimated distribution of thyroid doses based on screening tests for thyroid exposure among children and estimates from atmospheric dispersion simulations
(Solid line represents GM and dashed lines represent GM/$\sigma_g$ and GM × $\sigma_g$'; see main text)

dispersion simulations are close to the upper limits of the thyroid dose distribution obtained from the actual measurement data.

A comparison of estimates made with respect to evacuees is presented below. It should be noted that this comparison is intended for reference purposes only since the behavior of individuals is unclear.

Professor Tokonami of Hirosaki University and his group have reported the results of thyroid measurements that they conducted on residents of Namie-machi [16)]. The measurements were conducted on 62 individuals (45 from the coastal area and 17 from the Tsushima District). The maximum estimated thyroid dose was 33 mSv among adults and 23 mSv among children. These figures are a few dozen percent of the thyroid doses produced by the model cases for evacuations from Namie-machi (Nos. 7 and 13 in Table 2). The estimations produced by atmospheric dispersion simulations tend to result in larger doses. In some cases, however, thyroid dose estimates based on actual measurements (Table 1) conducted on residents of municipalities within 20 km of the plant are higher than those based on the model evacuation behavior cases from these municipalities.

### 4. Current Status of Reassessments of Early Internal Exposure Doses through Atmospheric Dispersion Simulations

The accuracy of internal exposure doses estimated by atmospheric dispersion simulations has yet to be fully verified. In the last fiscal year, therefore, the early internal exposure doses were reassessed for residents of Fukushima Prefecture by employing atmospheric dispersion simulations only for areas where data from actual measurements conducted on people could not be obtained (Table 1). Atmospheric dispersion simulations played a key role in the two regions of Nakadori and Aizu in Fukushima Prefecture. The estimated thyroid doses in the relevant municipalities are low (less than a few mSv in Fukushima-shi and Koriyama-shi, for instance). Taking into consideration the uncertainty associated with these estimates, it was considered appropriate at present to only indicate that doses are less than the confidence limit (assumed value: 10 mSv). As an exception, the dose estimations produced by atmospheric dispersion simulations were also referenced in the estimates for residents from Iwaki-shi. This was considered necessary backup because thyroid exposure screening tests were conducted on only a small number of children from Iwaki-shi. Estimations were assigned for Katsurao-mura and Minamisoma-shi by applying the available dose estimations based on actual measurements conducted on people in the neighboring municipality of Namie-machi.

## IV. Conclusion and Future Prospects

The NIRS investigated the application of atmospheric dispersion simulations in reassessing the early internal exposure doses for residents of Fukushima Prefecture who had been affected by the accident at TEPCO’s Fukushima Daiichi Nuclear Power Plant. The thyroid doses estimated through these atmospheric dispersion simulations and those estimated using data from actual measurements conducted on people had almost the same order of magnitude, but there was still a sizeable gap between them. For this reason, internal exposure dose estimations produced by atmospheric dispersion simulations should be regarded only as a point of reference.

Going forward, internal exposure doses may be estimated by effectively applying information on the behavior of individuals in a similar manner to that used in estimating external exposure doses. This method may be validated by estimating the doses through the use of atmospheric dispersion simulations for individuals based on available information concerning their behavior, thyroid measurements, and other data from actual measurements and then comparing them with dose estimations based on data from actual measurements. Doing this allows more realistic individual intake scenarios to be developed with reference to the outcomes of atmospheric dispersion simulations and so forth. The nuclide inhalation quantity is probably influenced considerably by differences in the behavior of individuals during the passage of a radioactive plume (i.e., a stream of air carrying radioactive materials just like smoke), such as whether they were indoors or outdoors and whether they were active or asleep. The author believes that fine-tuning models according to data on the behavior of individuals can significantly enhance the accuracy of internal exposure dose estimations. Given this, it is essential to enhance the accuracy of atmospheric dispersion simulations, and the author expects experts in this field to play an active role in achieving this.

This commentary is partly based on a project commissioned to the NIRS in FY2012 by the Ministry of the Environment to assess the impact of the Fukushima nuclear emergency. The Japan Atomic Energy Agency provided values calculated using WSPEEDI-II to facilitate this commissioned study of the internal exposure doses for iodine and other nuclides with a short half-life in the immediate aftermath of the nuclear accident.

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