Internal thyroid doses to Fukushima residents— estimation and issues remaining

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ABSTRACT

Enormous quantities of radionuclides were released into the environment following the disastrous accident at the Fukushima Daiichi Nuclear Power Plant (FDNPP) in March 2011. It is of great importance to determine the exposure doses received by the populations living in the radiologically affected areas; however, there has been significant difficulty in estimating the internal thyroid dose received through the intake of short-lived radionuclides (mainly, ^{131}I), because of the lack of early measurements on people. An estimation by the National Institute of Radiological Sciences for 1 April 2012 to 31 March 2013 was thus performed using a combination of the following three sources: thyroid measurement data (^{131}I) for 1080 children examined in the screening campaign, whole-body counter measurement data (^{134}Cs, ^{137}Cs) for 3000 adults, and atmospheric transport dispersion model simulations. In this study, the residents of Futaba town, Iitate village and Iwaki city were shown to have the highest thyroid equivalent dose, and their doses were estimated to be mostly below 30 mSv. However, this result involved a lot of uncertainties and provided only representative values for the residents. The present paper outlines a more recent dose estimation and preliminary analyses of personal behavior data used in the new method.

KEYWORDS: Fukushima Daiichi Nuclear Power Plant, accident, radioiodine, internal exposure, thyroid dose, behavior data

INTRODUCTION

On 11 March 2011, an unprecedented, large-scale nuclear accident at the Fukushima Daiichi Nuclear Power Plant (FDNPP), run by Tokyo Electric Power Company (TEPCO), was triggered by the failure of the cooling functions of the reactor cores following the massive tsunamis generated by the Great East-Japan Earthquake [1]. Enormous quantities of radionuclides were released into the environment from the damaged reactor cores, exposing the public to radiation through several pathways. Needless to say, it is of great importance to estimate the resulting radiation doses to the radiologically affected populations due to this accident. According to recent literature published about the Fukushima Health Management Survey (FHMS), the external doses to residents of Fukushima Prefecture during the first 4 months after the accident were estimated to be below 3 mSv for 99.4% of the 421 394 respondents to the Basic Survey questionnaire [2]. Internal doses to the residents have been also estimated by means of direct measurements with whole-body counters (WBCs); with this method, only 26 of 279 717 subjects examined were found to exceed 1 mSv in committed effective doses (CEDs) [3].

However, the latter result is only for the internal dose from radiocesium (^{134}Cs, ^{137}Cs). ^{131}Radioiodine (^{131}I with a physical half-life of 8.02 days), which was the largest contributor to the internal dose, was missed because of delay in the above WBC measurements. Since the accident, there has been growing concern about thyroid exposure in children due to the potential intake of ^{131}I and other short-lived radioiodine (^{132}I, ^{133}I), based on observations following the Chernobyl Nuclear Power Plant (NPP) accident.

However, unfortunately, the number of human measurements taken was limited (~1300), according to the published literature [4–7]. The present paper outlines the internal thyroid dose estimation by the National Institute of Radiological Sciences (NIRS) for 1 April 2012 to 31 March 2013 and subsequent attempts to improve the methodology for the most recent estimation.

INTERNAL THYROID DOSE ESTIMATION BY NIRS FOR 1 APRIL 2012 TO 31 MARCH 2013
Data used for the estimation

As mentioned above, the number of human measurements available for directly estimating the thyroid equivalent dose (hereinafter, the 'thyroid dose') due to the intake of ^{131}I is limited; thus, it has been necessary to use other information. The internal thyroid dose estimation by the NIRS for 1 April 2012 to 31 March 2013 was performed using a combination of information from the following three sources:

(i) Thyroid measurement data (^{131}I) obtained from 1080 children (under 15 years of age) examined in screening campaigns conducted in Kawamata town, Iitate village and Iwaki city by the Nuclear Emergency Response Local Headquarters at the end of March 2011 [4].

(ii) CED distributions (^{134}Cs ,^{137}Cs) of ~3000 adult subjects examined in the WBC measurements by the Japan Atomic Energy Agency (JAEA) in the period between 11 July 2011 and 31 January 2012 [8].

(iii) Time-series, ground-level air concentration maps (^{131}I) generated by the Worldwide version of the System for Prediction of Environmental Emergency Dose Information 2nd Version (WSPEEDI-II) with the latest source term at that time [9].

Among these, Source 1 was the only source of human data that was directly linked to the intake of ^{131}I; however, the thyroid measurements with non-spectrometric devices (i.e. NaI(Tl) survey meters) used for screening purposes were expected to involve a large degree of uncertainty. Moreover, the subjects were selected from only three municipalities outside a 30-km radius of the FDNPP. Source 2 incorporated a relatively large amount of data for residents from various municipalities, mostly located within the 30-km radius. Residents living within a 20-km radius of the FDNPP were ordered to evacuate from this area and those living within a 20- to 30-km radius of the FDNPP were ordered to shelter indoors [10]. These evacuation orders were issued on 12 March, the day after the earthquake. For the purpose of this study, it is necessary to determine an appropriate value for the intake ratio of ^{131}I to Cs. Source 3 was mainly used for estimations for residents in areas where no human data were obtained.

Procedures for the estimation

Using the above three sources and in collaboration with many experts from various institutes, the NIRS performed internal thyroid dose estimations for residents of the whole area of Fukushima Prefecture. In these estimations, inhalation was considered to be the dominant pathway for internal exposure. Details of the estimations based on each source are described as follows.

Estimation from direct thyroid measurements

Source 1 was believed to be the most reliable data of the three sources in terms of estimating the internal thyroid dose. Figure 1 displays measurement data obtained from the screening campaign for 1080 children [4]. The numbers of subjects for each place of measurement were: 631 for Kawamata town, 134 for Iwaki city, and 315 for Iitate village. The data in the figure are net readings from the devices used, which were determined by subtracting the dose rate measured for the body (at the shoulder) from that measured at the front surface of the neck for each subject. More than half of the subjects had zero readings. At the time of the screening campaign, priority was placed on identifying people who might receive significant thyroid exposure compared with the screening level (0.2 μSv h^{-1}), corresponding to a thyroid dose of 100 mSv per year for children. As a result, no subject exceeded this screening level.

Table 1 shows the 95th, 90th and 80th percentile values of individual internal thyroid doses (due to intake of ^{131}I) estimated by the NIRS for 1 April 2012 to 31 March 2013. In this estimation, two important items were revised from those originally chosen to determine the screening level. One was the age-dependent calibration factors used in converting the net readings to the ^{131}I radioactivity in the thyroid. The original factors were introduced based on one calibration phantom imitating the adult neck [11]. The thyroid container installed in this phantom has a volume of 20.5 ml, corresponding to the thyroid of the 'Reference Man' of the International Commission on Radiological Protection (ICRP) [12]. The original calibration factors for children were obtained from experiments in which these containers were filled with volumes of certified radioactive solution (^{133}Ba) corresponding to the average thyroid masses of children; i.e. 2.5 g for 1-year-old children and 6.1 g for 5-year-old children [13]. As a result, the solution was only at the bottom of the container; thus the experimental condition resulted in an unrealistic thyroid shape and also in a slight change in the distance between the thyroid and the neck surface, which might lead to a tendency to overestimate the ^{131}I thyroid content for children (whose thyroids are closer to the surface of the neck
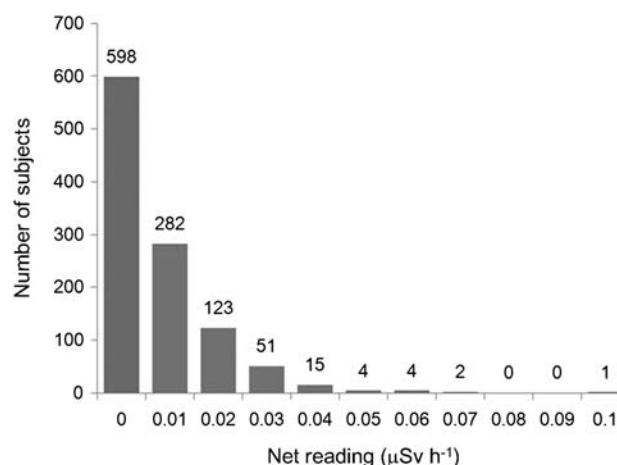

Fig. 1. Results of the screening campaign that examined thyroidal exposure for 1080 children.

than those of adults). Meanwhile, another study determined age-dependent calibration factors using neck phantoms imitating children of different ages, although the type of the detector used and the measuring unit ($\mu R\,h^{-1}$) were different [14]. Figure 2 shows the age-dependent calibration factors obtained from the above experiments and the previous study, with interoperations between ages, but these factors were both normalized to 30 kBq per $\mu Sv\,h^{-1}$ for adults. This value was equivalent to that originally obtained, and was also very similar to the result obtained in another study [15]. In the most recent dose estimation, averages of the factors from the two studies were used (see Fig. 2).

Another revised factor was the time of intake (inhalation) assumed in the intake scenario. The screening level was determined assuming chronic intake at a constant inhalation rate from 12 March to 23 March (12 days) 2011. However, this intake scenario was changed to an acute intake scenario on 15 March, when the largest release of radionuclides from the FDNPP was observed at many places in Fukushima and the neighboring prefectures [16, 17]. This change was considered reasonable in terms of conservative dose estimations because no significant elevation of the ambient dose rate was observed before 15 March in the municipalities where the screening campaign was conducted.

Needless to say, the accuracy of the thyroid measurements is also important in the dose estimation. The measurement data of the

Table 1. The 95th, 90th and 80th percentiles of thyroid doses to children

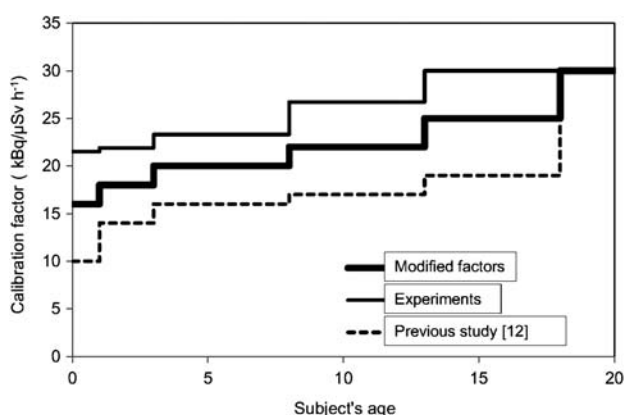| Municipality	Number of subjects	95th percentile[a]	90th percentile[a]	80th percentile[a]
Kawamata town	631	11.8	7.3	5.9
Iwaki city	134	20.9	15.9	10.6
Iitate village	315	20.4	14.7	9.9

[a]Unit: mSv.

Fig. 2. Age-dependent calibration factors for converting net readings to ^{131}I in the thyroid contents. (Modified factors: the averages of the calibration factors from the experiments and those from the previous study [14], see text.)
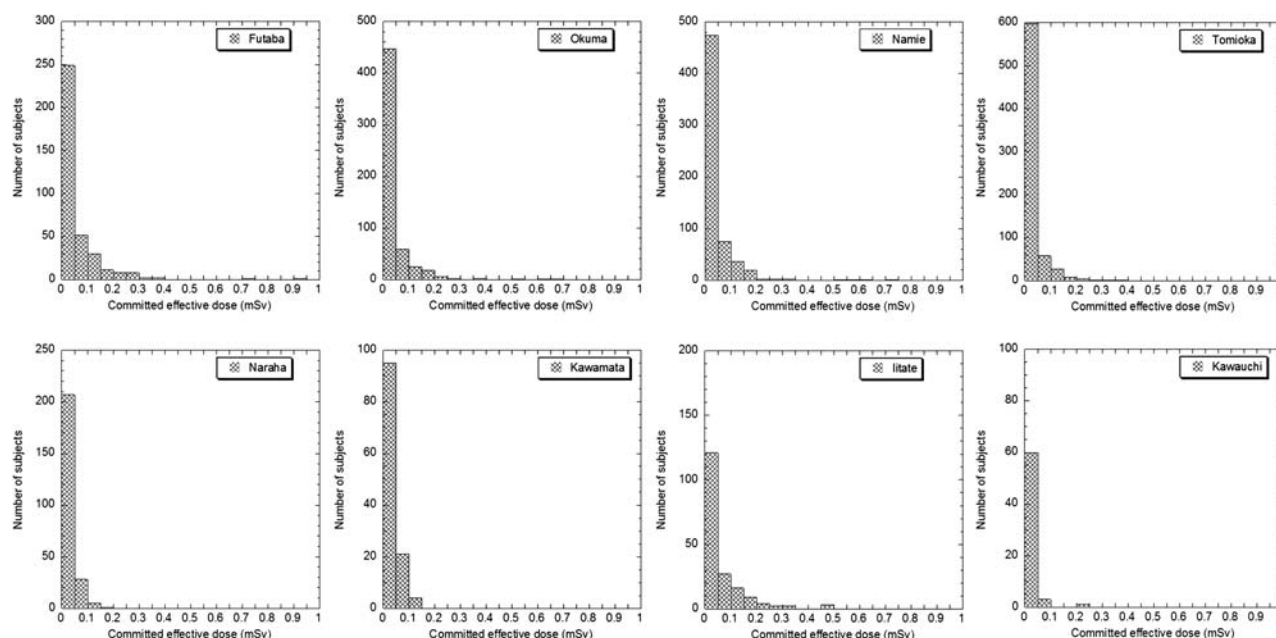
individuals are expected to contain uncertainties, such as in the counting statistics, the calibration factors, the measurement geometry and the interindividual variation in thyroid shape. In relation to the counting statistics, the average background levels for the subjects of Kawamata town, Iwaki city and Iitate village were $0.09\,\mu Sv\,h^{-1}$, $0.17\,\mu Sv\,h^{-1}$ and $0.12\,\mu Sv\,h^{-1}$, respectively [4]. The ambient dose rate in the measurement place was reported only for Iitate village ($0.1\,\mu Sv\,h^{-1}$) [18]. This suggested that most of the net readings existed within the statistical fluctuation of the background counts. The detectable thyroid dose would be ~10 mSv in the case of 5-year-old children when assuming that the detection limit was $0.02\,\mu Sv\,h^{-1}$. On the other hand, measuring the dose rate at the shoulder as background seemed to be reasonable in terms of taking into account the influence of radiocesium in the body on the measurements [19]. Ideally, this could have been done at the thigh, which would have yielded a similar shielding effect against ambient radiation to the neck [20, 21]. Although further studies are necessary on this issue and on the other uncertainty factors described above, the authors believe that there was no systematic bias in the thyroid measurements.

Estimation from WBC measurements

Source 2 was comprised of human data, as was Source 1, but it was not directly linked to the intake of ^{131}I. Moreover, only CED data for adult subjects ($\geq$18 years of age) of the WBC measurements were available because of ethical issues at that time. Accordingly, raw data related to these measurements, such as the whole-body contents (^{134}Cs, ^{137}Cs), the measurement date and each subject's gender and age, could not be used. The CEDs were evaluated based on the measured whole-body contents, along with a common intake scenario, namely acute intake by inhalation of Type F compounds on 12 March 2011 [8]. Figure 3 demonstrates the CED distributions of the adult subjects from various municipalities. Table 2 indicates the maximum, the 95th, the 90th and the 50th (median) CED values. The median CED value could not be obtained for most of the municipalities because of non-detection for many subjects in the prolonged WBC measurements.

The intake ratio of ^{131}I to ^{137}Cs was derived from human data for Iitate village and Kawamata town [22]. In these two municipalities, both the thyroid doses to children from ^{131}I and the CEDs to adults from ^{134}Cs and ^{137}Cs were obtained. These two doses could be linked to each other on the assumption that adults and children inhaled air with the same intake ratio of the two radionuclides at different breathing volume rates (i.e. $5.16\,m^3$ per day for 1-year-old children and $22.2\,m^3$ per day for adult males [23]). This relationship is illustrated in Fig. 4. The intake ratio of ^{131}I to ^{137}Cs was then derived by applying a thyroid dose and a CED at the same percentile to this relationship for the age group of 10-year-old children. The results are provided in Table 3.

Estimation from atmospheric dispersion simulation

Source 3 was used to complement the shortage of the human data described above. The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) performed the dose estimation for the Fukushima residents, mostly based on their

Fig. 3. CED distributions for adults from various municipalities.

Table 2. The maximum, 95th, 90th and 50th (median) percentile values of CED to adults

Municipality	Number of subjects	Maximum	95th percentile[a]	90th percentile[a]	50th percentile[a,b]
Futaba town	365	1.26	0.22	0.15	ND
Okuma town	561	0.68	0.15	0.10	ND
Tomioka town	696	0.36	0.11	0.08	ND
Naraha town	241	0.15	0.07	0.06	ND
Hirono town	210	0.26	0.12	0.10	ND
Kawauchi village	64	0.25	0.05	0.01	ND
Namie town	614	0.72	0.15	0.10	ND
Iitate village	184	0.48	0.22	0.17	0.03
Kawaamta town	120	0.13	0.08	0.07	0.01

[a]Unit: mSv.
[b]ND = not detected.

atmospheric transport and dispersion model (ATDM) analyses [24]. However, the use of Source 3 was minimized in the most recent dose estimation, due to uncertainties involved in ATDM simulations.

Figure 5 shows the thyroid dose map based on the WSPEEDI-II for hypothetical 1-year-old children who inhaled ^{131}I outdoors until 31 March 2011 [25]. This result indicates that the thyroid dose by inhalation was not significant in the Nakadori and Aizu regions (the central and western parts of Fukushima Prefecture), where no human data were obtained. Figure 6 shows comparisons between the thyroid dose distributions of the children and the thyroid doses obtained from WSPEEDI-II for each municipality: Kawamata town (Panel A), Iwaki

city (Panel B) and Iitate village (Panel C). Since no information on personal behaviors of the children was available at the time of the more recent dose estimation, the latter doses were calculated as the geometrical mean (GM) values of the doses to hypothetical 5-year-old children who continued staying outside until the day of the measurement at the grid (of the WSPEEDI-II) nearest to the local government office at each municipality and its eight surrounding grids; the bands in the figure correspond to GM/σ_g and $GM \times \sigma_g$. As shown in the figure, the simulation results give the upper limits of the thyroid dose distributions from the human data. This result was considered reasonable because possible dose reduction factors due to sheltering indoors or evacuation were not taken into account in the simulation.
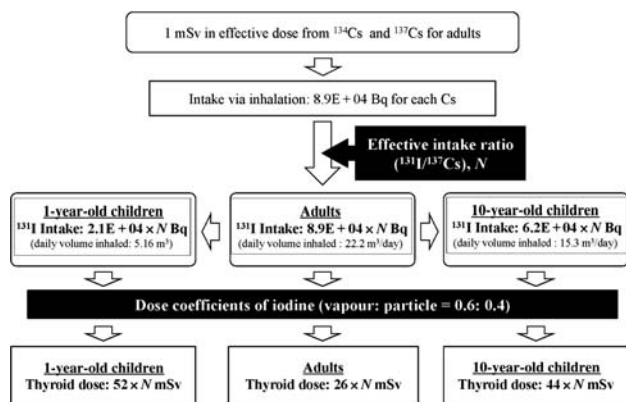
Fig. 4. Relationship between the thyroid doses to children and the effective doses to adults [22].

Table 3. Derived intake ratios of ^{131}I to ^{137}Cs [22]

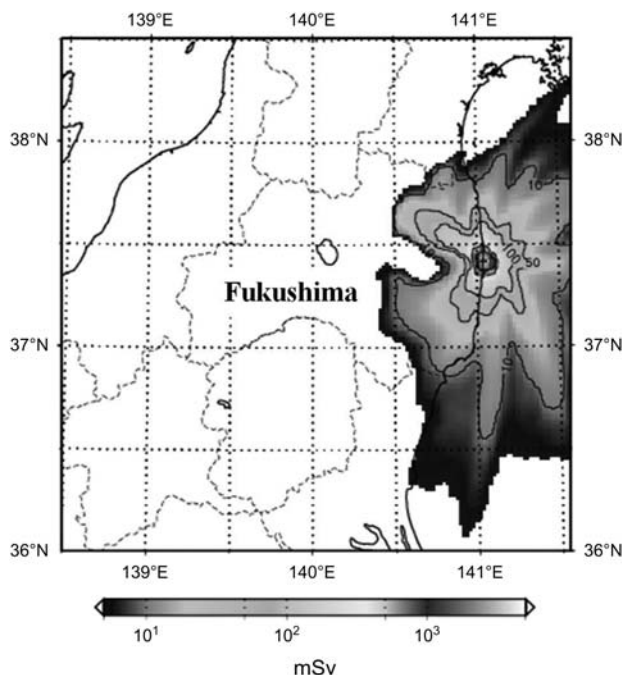| Municipality	95th percentile	90th percentile	80th percentile
Kawamata town	3.3	2.4	2.7
Iitate village	2.1	2.0	2.3

Fig. 5. Thyroid dose map calculated by WSPEEDI-II (due to inhalation of ^{131}I until 31 March 2011) [25].

Summary of the estimation

By combining the above three sources, the internal thyroid doses to Fukushima residents were estimated as shown in Table 4. The figures in the table are given as a 90th percentile value (rounded to the nearest 10%) of the internal thyroid doses to 1-year-old children and adults, excluding the municipalities where the simulation was applied to the estimation. The estimation mostly depends on the WBC measurements (Source 2). The intake ratio of ^{131}I to ^{137}Cs was determined to be 3, based on the result (Table 3). A typical value of the 90th percentile CED (adults) was ~0.1 mSv (Table 2). From this, the thyroid doses to 1-year-old children and adults were calculated as 17.2 mSv and 8.6 mSv, respectively, using the determined relationship (Fig. 4) in addition to the dose contribution from radionuclides other than ^{131}I (10%), based on the continuous air sampling data collected at JAEA's site in Tokai village, Ibaraki Prefecture (located ~110 km south of the FDNPP) [17]. The thyroid dose to 1-year-old children was calculated as follows: 0.1 mSv × 52 × 3 × 1.1 = 17.2 mSv. Regarding Minami-soma city and Katsurao village, the thyroid doses were assumed to be at the same level as those for Namie town (neighboring these municipalities). Regarding Iwaki city, the simulation result was more heavily weighted in the estimation than the screening campaign result because the number of subjects in the latter was small in comparison to the youth population (under 15 years of age) in Iwaki city. In summary, the internal thyroid dose was expected to be relatively higher in residents of Futaba town, Iitate village and Iwaki city than in the rest of the municipalities. Their thyroid doses were estimated to be mostly below 30 mSv, which is comparable with the estimations of other studies [5, 6].

REMAINING ISSUES AND NEW APPROACH FOR THE ESTIMATION

The internal thyroid dose estimation by the NIRS for the fiscal year 1 April 2012 to 31 March 2013 showed only the upper dose levels for Fukushima residents. Needless to say, a more detailed dose estimation has been needed, in particular to clarify whether anyone in the area received significant radiation exposure. UNSCEAR performed an independent dose estimation and reported that the average thyroid dose (including the external thyroid dose) to 1-year-old children of the evacuated settlements could reach ~80 mSv, although considerable overestimations in their results were expected [24]. This large discrepancy between the estimations of the NIRS and UNSCEAR occurred because the UNSCEAR method included the dose contribution from ingestion, whereas the NIRS method did not. There has been much discussion among Japanese experts regarding this issue. As a result, it was concluded that the potential ingestion dose should be individually estimated based on personal information about food consumption after the accident. Otherwise, as in the case of UNSCEAR, an ingestion dose that might be significant only for a few people would be used to estimate the general dose of residents. The ingestion dose should be trivial for most residents because of prompt regulations concerning the distribution and consumption of food and drinking water by the Japanese authorities [26] and voluntary radiation protection measures taken by individuals (e.g. sheltering indoors, drinking bottled water). The results for the screening survey also suggested that the internal thyroid doses to the subjects were small, even considering the possibility of ingestion; however, careful investigation of the diet of these and other residents is needed.
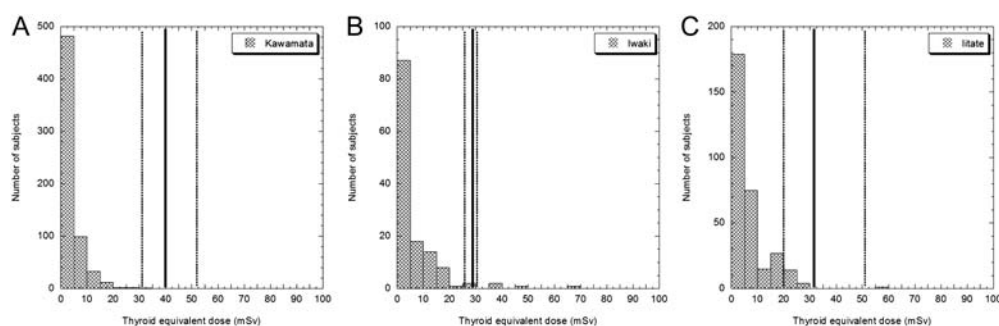
Fig. 6. Internal thyroid doses to children: Panel A for Kawamata town, Panel B for Iwaki city and Panel C for Iitate village [25]. Histogram: doses from human measurements. Solid line. GM; right and left dotted lines, GM × σg and GM/σg (see text).

Table 4. Internal thyroid doses to 1-year-old children and adults. Rounded 90th percentile values, excluding the municipalities where the simulation applied

Municipality	1-year-old children[a]	Adults[a]	Method[b]
Futaba town	30	10	WBC
Okuma town	20	<10	WBC
Tomioka town	10	<10	WBC
Naraha town	10	<10	WBC
Hirono town	20	<10	WBC
Namie town	20	<10	WBC, Ref. [5]
Iitate village	30	20	Thyroid, WBC
Kawamata town	10	<10	Thyroid, WBC
Kawauchi village	<10	<10	WBC
Katsurao village	20	<10	Same as Namie
Iwaki city	30	10	Simulation, Thyroid
Minami-soma city	20	<10	Same as Namie
Other areas in Fukushima Pref.	<10	<10	Simulation

[a]Unit: mSv.
[b]Thyroid = Thyroid measurements (Source 1), WBC = Whole-Body Counter measurements (Source 2); simulation, WSPEEDI-II (Source 3).

To address the issues described above, the authors have proposed a new method, shown in Fig. 7. As shown in the figure, the main feature of the proposed method is characterizing of subject groups depending on their behavior patterns and internal dose levels, and determining representative doses for each subject group. These representative doses could be assigned to people who were not measured, but who acted in a similar way to those who were measured. The personal behavior data used in this method are basically the same as
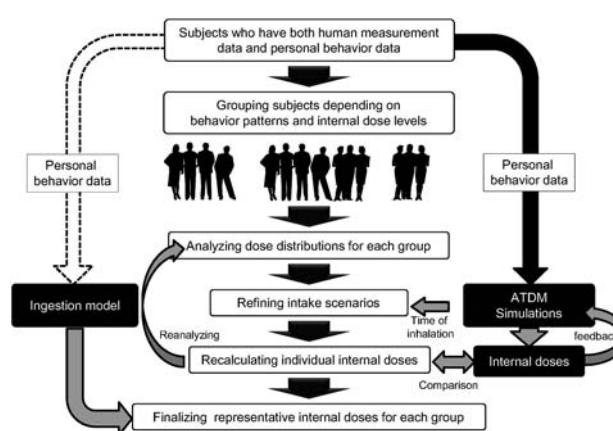

Fig. 7. The proposed method for the internal dose estimation using personal behavior data.

those used as input data for the NIRS external dose estimation system, which was developed to perform the Basic Survey that was one of the main components of the FHMS [27]. These data included the whereabouts (the place name and its latitude and longitude) and time spent indoors, outdoors or moving during the first four months after the accident. Information on diet has also been roughly collected by questionnaires in the Basic Survey [28], and might to be able to be utilized in the future. The behavior data that was obtained for people within the year following the accident became available through the approval of the research ethics committee of NIRS and FMU in 2013. To the present, NIRS has received 412 personal behavior datasets from FMU, including those for 310 of the 1080 subjects of the screening campaign and 112 of the 174 subjects of the pilot survey that was conducted by NIRS during the period between 27 June and 28 July 2011. The authors are now analyzing these data, and we present examples of the preliminary results here.

Figure 8 shows the whereabouts of the subjects of the screening campaign on 17 March and on 21 March 2011, including the municipalities in which each person was examined, and whether they were within or outside the Fukushima Prefecture (missing data for several subjects). As shown in the figure, a significant proportion of the subjects evacuated from their homes shortly after
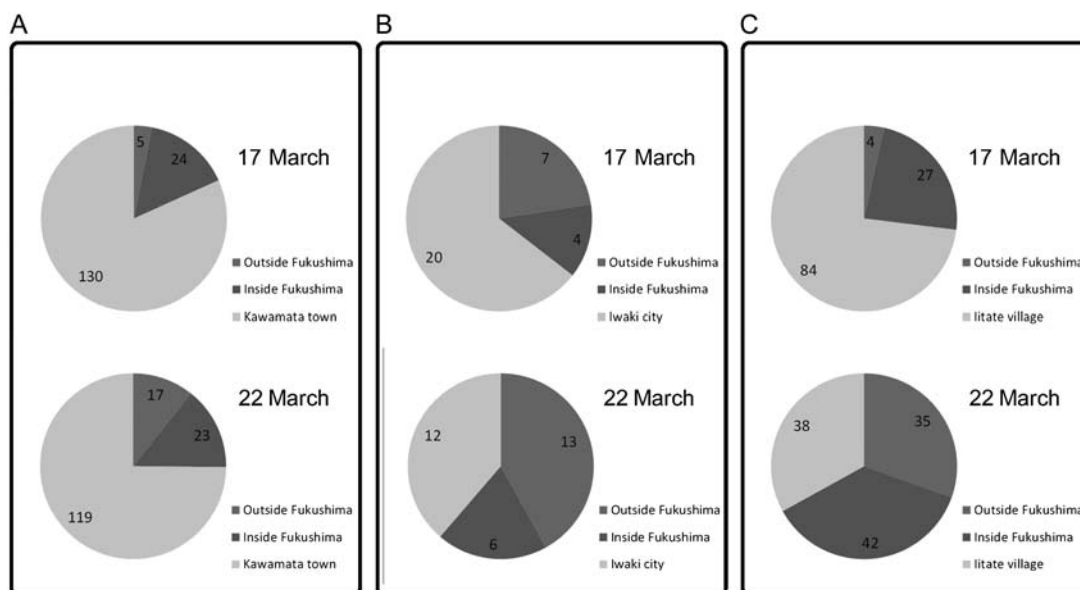
Fig. 8. Locations of the subjects of the screening campaign: Panel A, Kawamata town; Panel B, Iwaki city; Panel C, Iitate village.

House (11 March)
Shelter (12–26 March)
Fukushima city (26 March–)

House (11–14 March)
Nihonmatsu city, Shelter (15 March – 10 April)
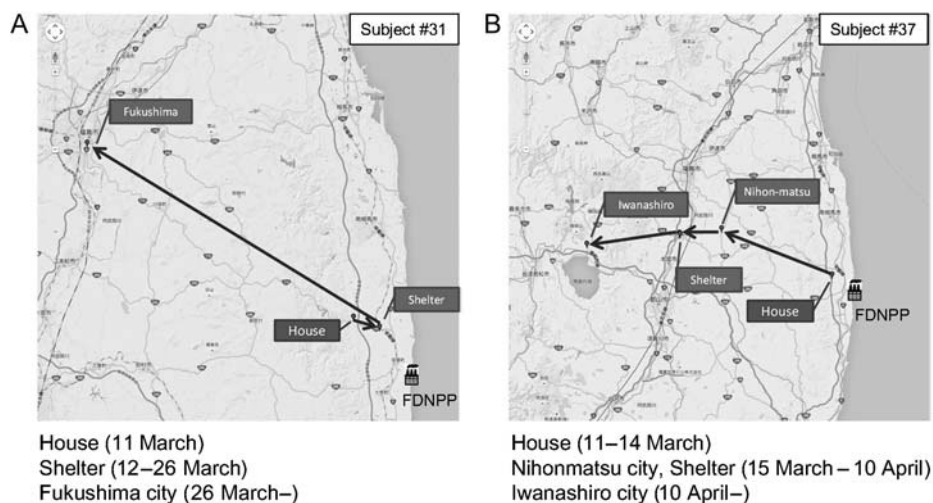Iwanashiro city (10 April–)

Fig. 9. Locations of the subjects of the screening campaign: Panel A, Kawamata town; Panel B, Iwaki city; Panel C, Iitate village.

the accident, although evacuation was not requested in Kawamata town, Iwaki city or Iitate village. This means that these voluntary evacuees were probably less exposed than those who continued to stay in their home municipalities until the time of the screening campaign; this might be a major reason for the relatively low doses to the 1080 subjects. Because of this, it would be important to clarify whether the time of evacuation—in particular, whether subjects left before or after the significant release events of radionuclides on 15 March and on 21–22 March—influenced the dose [22]. This will be examined in the authors' next study.

Figure 9 shows personal behaviors for the two subjects whose CEDs (from ^{134}Cs and ^{137}Cs) were found to be relatively high in

the pilot survey. These two people were both residents of Namie town, where an evacuation order was issued on the morning on 12 March by the local government office [10]. From the personal behavior data of the subjects of the pilot survey, it was confirmed that most people evacuated promptly according to this order and moved to various places further from the 30 km radius within March (data not shown here). Contrary to that, these two people delayed evacuation, as illustrated in the figure. This could be related to their internal doses; however, it does not appear to be easy to associate personal behavior patterns with the level of the dose. For the residents whose evacuation was delayed, including the two people mentioned, the magnitude of their intake on 12 March was
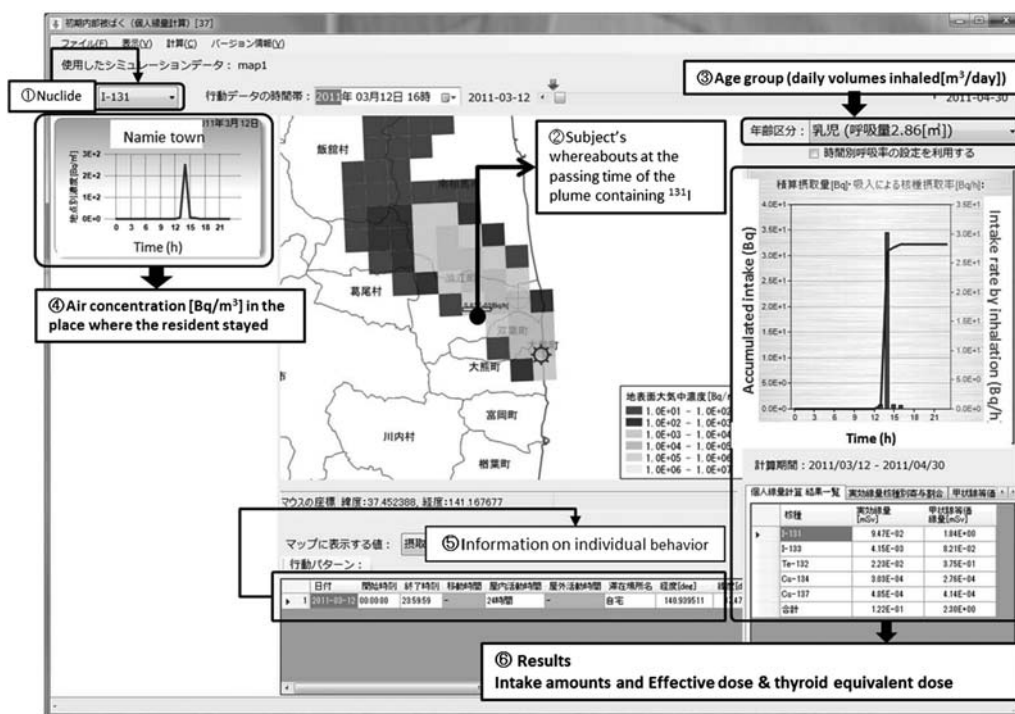
Fig. 10. Main screen of the prototype system for the internal dose estimation [25].

crucial in the dose estimation because the dose contribution from the short-lived radionuclides other than ^{131}I is expected to have been significant. According to Shinkarev *et al.* [29], this dose contribution is expected to have been as great as 30–40% of the inhalation intake from as early as 12 March.

Figure 10 shows the main screen of the prototype system for the internal dose estimation based on the WSPEEDI-II and personal behavior data [25]. This system can visualize the ground-level air concentration of radionuclides (^{131}I, ^{137}Cs) and the whereabouts of the person at the same time, and compute the internal dose by inhalation for a specified period of time. Although there is currently a large discrepancy between the individual internal doses from the human measurements and those from the system (data not shown here), this could be improved by updated simulations that take into account several modifiers of the intake, such as the indoor shielding factor, the ventilation rate depending on the exertion level, and so on. As described above, the personal behavior data will be useful for improving the internal dose estimation and also for identifying people who have potentially received significant internal exposure. It will be necessary to carry out further analysis of the personal behavior data. The proposed method will be implemented based on the results of this analysis as presented here.

CONCLUSION

The NIRS published internal thyroid dose estimation results for Fukushima residents in 1 April 2012 to 31 March 2013. This estimation was performed using a combination of direct human measurements on 1080 children (^{131}I) and ~3000 adults ([134]Cs, ^{137}Cs), along with ATDM simulations. They concluded that the highest doses were expected to affect residents of Futaba town, Iitate village and Iwaki city, and their doses were estimated to be mostly below 30 mSv. However, this result involved a lot of uncertainties and provided only representative values for the residents of each municipality. To address the remaining issues, the authors have proposed a new dose estimation method using personal behavior data and have shown examples of the preliminary analyses. These results will be reported by the authors at a future date.

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