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Comparison between external and internal doses to the thyroid after the Fukushima Daiichi Nuclear Power Plant accident

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ABSTRACT

To analyze the association between radiation dose and thyroid cancer after the 2011 Fukushima Daiichi Nuclear Power Plant (FDNPP) accident, external doses have often been used because of the difficulty to estimate internal thyroid doses individually due to the lack of human data. However, no evaluation has been made as to whether external dose is a good surrogate marker for internal thyroid dose individually. This study aimed at analyzing the relationship between external doses and internal thyroid doses estimated by recently developed methodology. For four municipalities affected by the accident, 200 individuals aged under 20 at the time of the accident per municipality were randomly selected, and their external and internal thyroid doses and their ratios were estimated individually. In a separate analysis, median and arithmetic mean values for external thyroid doses estimated for persons of 16 municipalities that included the above four were compared with those for previously estimated internal thyroid doses. The ratios of the median of internal thyroid dose to that of external thyroid dose in these 16 municipalities ranged from 0.56 to 13.8 for 15-year-old children and 0.91 to 21.1 for 1-year-old children. No consistent relationship between external and internal thyroid doses was found in all 16 municipalities. Thus, thyroid doses from both external and internal exposures should be used to analyze the association between radiation dose and thyroid cancer detection rates for persons who lived in Fukushima Prefecture at the time of the FDNPP accident. (240).

Keywords: thyroid; Fukushima Daiichi accident; internal dose; external dose

INTRODUCTION

Large amounts of radioactive materials including radioiodine were released in the Fukushima Daiichi Nuclear Power Plant (FDNPP) accident. Because radioiodine tends to accumulate in—and irradiate—the thyroid gland, there is concern among residents that children might suffer from thyroid cancer in the future [1]. Therefore, the Fukushima Prefectural Government and Fukushima Medical University (FMU) began an ultrasound thyroid examination campaign as a part of the Fukushima Health Management Survey (FHMS). The campaign was launched in October 2011 to cover about 360 000 residents who were less than 19 years old at the time of the accident [2]. As of 30 September 2021, 274 suspected or definite thyroid cancers have been found [3]. To elucidate the causal relation between the accident and thyroid cancers, it is essential to analyze the association between radiation dose and thyroid cancer.

For this purpose, it is desirable to use individual thyroid equivalent doses or absorbed doses. However, in the FDNPP accident, thyroid dose due to internally deposited radionuclides (hereafter, called 'internal thyroid dose') had large uncertainty mainly due to the lack of early accident stage human measurement data [4]. Thus, the following types of doses have been used as a surrogate for thyroid doses in the association studies between radiation dose and thyroid cancer detection rates.

Many data have been accumulated on ambient dose rate and radionuclide deposition density through large scale environmental surveys. These values were used by Yamamoto *et al.* [5] and Toki *et al.* [6] to detect the radiation effects on thyroid cancer. However, these parameters do not necessarily reflect individual doses, because individual doses depend on people's behaviors as well as environmental radiation levels of their residential areas. Thus, it is more appropriate to use external dose as a parameter reflecting individual behaviors as well as the environmental radiation levels of residential areas. Individual external effective doses in an early stage after the accident have been estimated by a survey (called the 'Basic Survey') as a part of the FHMS [2]. Some previous studies have investigated the association between thyroid cancer detection rates and individual or regional external doses estimated by the Basic Survey [7–9].

Regarding internal thyroid doses, there were large uncertainties in the dose estimation for several years after the FDNPP accident, and regional- or district-specific thyroid doses estimated by the World Health Organization (WHO) [10, 11] and the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) [12] were much larger than those doses based on thyroid measurements. Thus, efforts for reconstructing internal thyroid doses have been continuously made. Ohba *et al.* [13] estimated internal thyroid doses due to inhalation for persons of seven municipalities using individual resident behavior patterns after the accident together with an atmospheric transport, dispersion and deposition (ATDM) model. They also estimated dose due to ingestion of drinking water in one municipality where ingestion dose was expected to give a significant contribution. The estimated internal thyroid doses totaled from inhalation and ingestion were in good agreement with those estimated by direct thyroid measurements conducted soon after the accident. Such progress in the reconstruction of internal thyroid dose was reflected in the UNSCEAR 2020 report [14], in which more realistic thyroid absorbed doses were estimated, compared with those in its 2013 report [12].

Suzuki [15] compared internal thyroid doses estimated by the methodology employed by Ohba *et al.* [13] and the external doses by the Basic Survey for several municipalities and found that they were not correlated. External dose is mostly caused by radionuclides deposited onto the ground [14]. Rain and snow enhanced the deposition of radionuclides onto soil but they did not influence the inhalation dose.

Although Suzuki [15] compared the internal and external doses for 12 municipalities, no statistical analysis was made for the comparison. Thus, this study aims at making more detailed comparisons between external and internal thyroid doses for the municipality and individual levels. From the comparisons, considerations are made about whether or not external dose is suitable as an explanatory parameter to analyze the association between radiation dose and thyroid cancer.

MATERIALS AND METHODS

Approvals were obtained from the Institutional Review Boards of the International University of Health and Welfare (IUHW: 13-B-185, August 2016, 13-B-339, March 2019, 20-B-433, October 2020) and FMU (No.29100, August 2018; No.2019-003, July 2019, 2020-235, December 2020) for the study.

Thyroid equivalent doses due to external and internal exposures (hereafter, called external thyroid dose and internal thyroid dose, respectively) were compared in the following ways.

Estimation of external thyroid doses

External thyroid doses were estimated based on individual effective doses estimated by the Basic Survey. The method for dose estimation by the Basic Survey has been described in detail elsewhere [16]. Briefly, it was a self-administered questionnaire survey that asked eligible people to record and send back information on their behaviors (including time spent indoors and outdoors and time of moves) in the first 4 months after the March 2011 accident. Target population of the Basic Survey was people who were registered as residents in Fukushima Prefecture from 11 March to 1 July 2011 (around two million people). The respondents' behavior records were digitalized, and a computer program calculated individual effective doses due to external exposure by superimposing the behavior records with daily ambient dose equivalent rate maps. Effective dose depends on body size, even if an individual is exposed in the same irradiation geometry. Thus, the Basic Survey estimated effective doses considering age of each individual. For example, effective dose for 1-year-old infants is estimated to be 1.26 times larger than that for adults in the same irradiation geometry [17]. The individual doses for the first 4 months were calculated for 465 999 questionnaire respondents as of 31 March 2019 [18].

Considering the uncertainty of dose estimation, the calculated dose values were rounded to the first decimal place for doses of less than 10 mSv and to the ones place for doses of more than 10 mSv. The rounded values of dose estimates have been stored in a database which is open to researchers. For doses less than 0.1 mSv, they are stored as 'less than 0.1 mSv' without any numerical data. Data used in this study were extracted from the database. A certain numerical value should be assigned to calculate arithmetic means. Here, 0.05 mSv was assigned for 'less than 0.1 mSv.'

The Basic Survey calculated individual effective doses due to external exposure based on ambient dose rate maps. Isotropic irradiation (ISO) geometry was assumed when converting the ambient dose rate to effective dose rate. ICRP Publication 74 [19] presents thyroid absorbed dose per unit air kerma free-in-air and effective dose per unit air kerma free-in-air. By comparing them, the ratio of thyroid equivalent dose to effective dose (called CF, hereafter) was calculated. It is around 1.1 in the case of the ISO geometry of external exposure (gamma rays with energies of around 100 keV to 1 MeV). The recently published ICRP Publication 144 [20] presents organ and effective dose rate coefficients for members of the public resulting from environmental external exposures to radionuclide emissions of photons. It was confirmed that the CF derived from ICRP Publication 74 was consistent with that from ICRP Publication 144 (Supplementary Text and Supplementary Table S1).

Estimation of internal thyroid dose

Estimation methodologies for both inhalation and ingestion doses to the thyroid have been reported elsewhere [13, 21]. Briefly, inhalation doses were estimated by combining the behavior records for respondents to the Basic Survey questionnaire with a spatiotemporal radionuclides concentration database constructed by a kind of ATDM model simulation, Worldwide version of System for Prediction of Environmental Emergency Dose Information_2019 database (WSPEEDI_2019DB) [22]. In addition, reduction of inhalation dose by staying indoors, thyroid uptake rates appropriate for the Japanese population, and contributions of short-lived radionuclides other than ^{131}I to thyroid doses were considered for the dose estimation [13]. Major parameters used for inhalation dose estimation are listed in Supplementary Table S2. Ingestion doses were estimated by combining the behavior records with a meta-database of spatiotemporal ^{131}I concentrations (Bq/m^3) in tap water, where hourly ^{131}I concentrations from 6 a.m. on 12 March to 12 p.m. on 25 March 2011 in 3 km grid areas of WSPEEDI_2019DB were calculated with a one-compartment model. The thyroid uptake rates appropriate for the Japanese population were also reflected in the ingestion dose estimation [21, 23]. Major parameters used for ingestion dose estimation are listed in Supplementary Table S3.

ICRP Publication 72 [24] gives age-specific inhalation/ingestion dose coefficients for 3-month-olds, 1-year-olds (1-yo), 5-year-olds (5-yo), 10-year-olds (10-yo), 15-year-olds (15-yo) and adults. Based on this categorization, each dose coefficient was applied to the following individuals of the stated age at the time of the accident: 1-yo (from 0-yo to 2-yo), 5-yo (more than 2-yo to 7-yo), 10-yo (more than 7-yo to 12-yo), 15-yo (more than 12-yo to 17-yo) and adults (more than 17-yo). Age at the time of the accident was extracted from the database, together with the behavior data. Because the age at the time of the accident was obtained as a one-digit year, the dose coefficient of 1-yo was applied to the 0-yo to 2-yo. The corresponding dose coefficients were used for calculating internal thyroid doses for individuals.

Comparison of external and internal thyroid doses at an individual level and calculation of their ratio

For a comparison at the individual level, four municipalities were selected: Iwaki City, Minamisoma City, Date City and Tamura City. Iwaki and Minamisoma Cities are located in coastal areas, while Date and Tamura Cities are located inland (Fig. 1). Here, municipalities facing the ocean were defined as the coastal areas and other municipalities were defined as the inland areas. In the coastal areas, radioactive materials in the air were deposited mainly by a 'dry-deposition' mechanism at the time of the accident. On the other hand, in the inland areas, radioactive materials were deposited by a 'wet-deposition' mechanism, i.e. coprecipitating with rain and snow falls. Figure 1 shows the locations of 16 municipalities studied including the four mentioned above. Iwaki and Minamisoma Cities have the largest and second largest populations among the coastal areas, respectively, and a sizable fraction of children in these municipalities were evacuated after the accident. Date and Tamura Cities have the largest and second largest populations among the studied municipalities of inland areas. Most of the children in these municipalities were not evacuated. For these reasons, these four cities were selected as typical municipalities of the coastal and inland areas, respectively.

Considering the time needed for the calculation of individual internal thyroid doses, it was not practical to estimate internal thyroid doses for all individuals who submitted the behavior records in response to the Basic Survey. Thus, for each municipality, individual behavior data of 200 residents who were less than 20 years of age at the time of the accident were randomly selected. 'Systematic sampling' was used for the random sampling method. In this method, a sample interval (k) was decided by dividing the population size of each municipality by the sample size ($n = 200$). The interval indicates that every k^{th} individual was sampled in a subject list for each municipality. Next, a random point was determined within the range from 0 to k. For example, if $k = 20$ and the random point started at 2, the 2nd, 22nd, 42nd, ..., 182nd individuals were sampled from the subject list. Some of these individuals had behavior records for less than 4 months. In such cases, external doses were estimated for the actual period (i.e. less than 4 months) corresponding to the behavior records. Such individuals were excluded from further analysis to keep the dose comparison for the same 4-month period. Regarding individuals with the 4-month behavior records, the 4-month external effective doses were multiplied by 1.1 to convert them to external thyroid doses during the same period.

For the individuals who had 4-month behavior records, internal thyroid dose was calculated using the methodology described before. Then, external and internal thyroid doses were compared for each individual. Spearman rank correlation was used to test significance of the correlation between external and internal thyroid doses. The ratio of internal thyroid dose to external thyroid dose was also calculated for each individual. Analyses were performed with Origin Pro 2021 (OriginLab Corporation, Northampton, USA). All significance levels were set at 5%.

Comparison of external and internal dose at a municipality-level

Another study applied the methodology for estimating internal thyroid doses to 3256 individuals randomly selected from each of 16 municipalities around the FDNPP and estimated distributions of internal thyroid doses for these municipalities [23]. Arithmetic mean, median and 25th and 75th percentiles of internal thyroid doses were estimated for five different age categories (1-yo, 5-yo, 10-yo, 15-yo and 20-yo) for each municipality. These doses were used for the present study.

For estimation of external thyroid doses, all respondents to the Basic Survey under 20 years of age were selected for each of the 16 municipalities and their 4-month doses were extracted from the database. The numbers of extracted doses for each municipality are shown in Table 1, together with the number of persons under 20 years of age. The population data were taken from the 2010 population census [25], which were considered to be close to the population data at the time of the accident (March 2011).

As shown in Table 1, the ratio of external effective doses for individuals aged 0 to 2 to those aged 0 to 19 ranged from 0.71 to 1.13 (average: 0.94). Similarly, the ratio of doses of individuals aged 13 to 17 to those aged 0 to 19 ranged from 0.87 to 1.35 (average: 1.06). Although the individual external doses of two different age groups (ages 0–2 vs. ages 13–17) was significantly different ($P < 0.05$), the age dependence was relatively small. Also, the minimum number of extracted dose data among the 16 municipalities was 107 for Katsurao Village, which had a total population at the time of accident of around 1500. Considering the age-dependence of external effective dose and the number

Fig. 1. Locations of 16 studied municipalities in Fukushima Prefecture, Japan.

Table 1. Age dependence of external doses based on the Basic Survey

Area (coastal or inland)	Municipality	No. of individuals from 0 to 19 years of age	Extracted number of doses for individuals <20 years of age	Average dose for 0-yo to 2-yo / Average dose for 0-yo to 19-yo	Average dose for 13-yo to 17-yo / Average dose for 0-yo to 19-yo
Coastal area	Shinchi	1520	649	0.93	1.06
	Soma	7011	3061	0.99	1.01
	Minamisoma	12 796	5973	0.88	1.14
	Namie	3693	2271	0.78	1.16
	Futaba	1241	758	0.90	1.02
	Okuma	2375	1292	0.97	0.87
	Tomioka	3140	1712	1.00	0.91
	Naraha	1454	780	0.71	1.04
	Hirono	1093	468	0.89	1.11
	Iwaki	63 812	24 185	0.95	1.04
Inland area	Date	11 726	5110	1.01	1.00
	Iitate	1060	546	0.94	1.17
	Kawamata	2441	899	0.97	1.04
	Katsurao	249	107	1.00	1.35
	Tamura	7277	2144	1.13	1.07
	Kawauchi	352	200	0.91	1.04
	Average	-	-	0.94	1.06

of dose data, all data for individual external doses for ages 0 to 19 were used for the present study. After multiplying the individual effective doses by 1.1 for conversion to external thyroid doses, arithmetic mean and median of external thyroid doses were estimated for each municipality.

For comparing dose distributions of external and internal thyroid doses, the ratios of arithmetic mean of internal thyroid dose to that of external thyroid dose were calculated for each municipality. Similarly, the ratios for median values were also calculated. Similarity of these ratios among municipalities would suggest that external thyroid dose

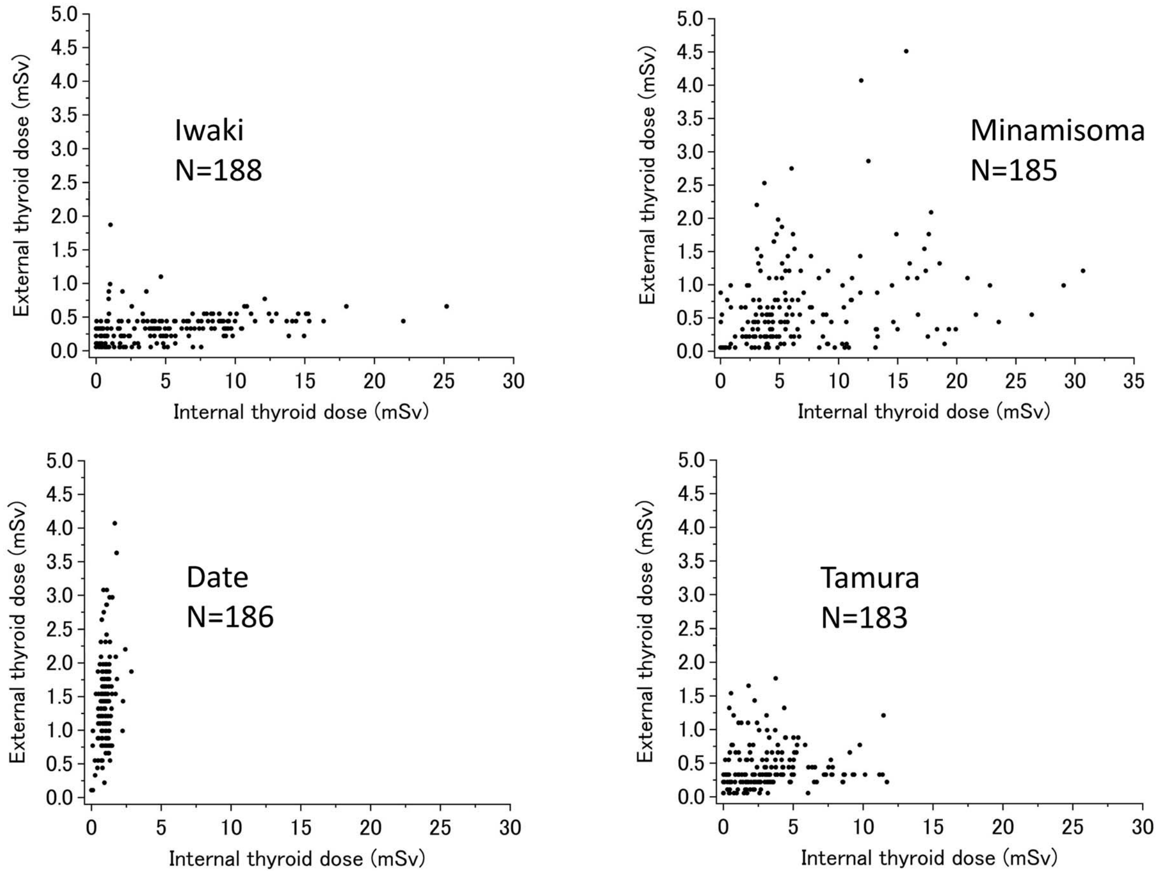

Fig. 2. Correlation between external and internal thyroid doses for randomly selected individuals after the exclusion for each of four municipalities.

could be an indicator of total thyroid dose. Because the internal thyroid dose significantly depends on age, internal thyroid doses for 1-yo and 15-yo were taken from the literature [23] and used for this calculation. In addition, the percentages of external thyroid dose to total thyroid dose (for 1-yo and 15-yo, respectively) were calculated for each municipality.

The ratios and percentages were expected to be dependent on geographical location of each municipality. Thus, the association between geographical location of each municipality such as the coastal and inland areas from the FDNPP and the calculated ratios and percentages was also considered.

Comparison between the ratios for individual and municipality levels

The ratios of internal thyroid dose to external thyroid dose were estimated both from individual and municipality levels, as described before. For the four municipalities where 200 individuals per municipality were randomly selected, the ratios estimated from the selected individuals were compared with those estimated from data obtained at the municipality level to see if both ratios were consistent with each other.

RESULTS

Comparison of the ratio of external to internal thyroid doses at the individual level

Figure 2 shows a comparison between external and internal thyroid doses at the individual level. Since persons who had behavior records for less than 4 months were excluded from the 200 randomly selected subjects for each municipality, data for the number of individuals after the exclusion (N) are plotted in the graphs. Average ages in March 2011 for these individuals were almost the same among the four municipalities (Iwaki: 9.8 ± 5.3, Tamura: 9.9 ± 6.0, Date: 9.4 ± 5.4, Minamisoma: 9.0 ± 5.8, Average ± SD [in years]). Although the correlation was significant ($P < 0.05$) for all four municipalities, the correlation coefficient ranged from $r_s = 0.204$ (Date City) to $r_s = 0.440$ (Iwaki City). The correlation coefficient was $r_s = -0.116$ when all subjects (after exclusion) from the four municipalities were summed up (Fig. 3).

Boxplots for individual internal and external thyroid doses (after exclusion) for each municipality are shown in Fig. 4. The ratio of the median of internal thyroid doses to that of external thyroid doses ranged from 0.69 (Date City) to 12.8 (Iwaki City).

Figure 5 shows distributions for each of the four municipalities of the ratio of internal thyroid dose to external thyroid dose for randomly selected subjects (after exclusion). Similar to the results for Fig. 4, the

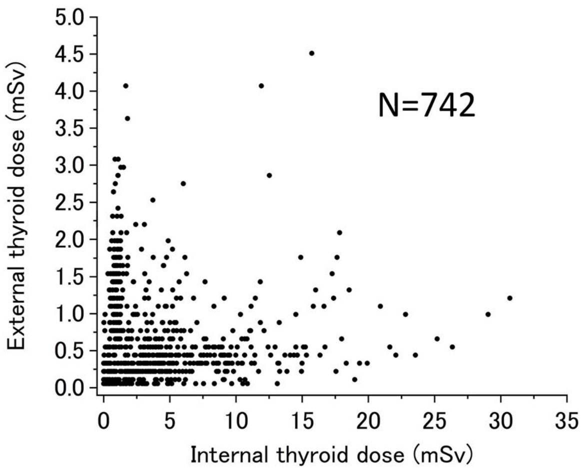

Fig. 3. Correlation between external and internal thyroid doses for all individuals selected after the exclusion from the four municipalities.

median values differed among the four cities. The ratios for the coastal Iwaki and Minamisoma Cities were higher than those for the inland Date and Tamura Cities. The ratios were almost the same as those estimated from median values shown in Fig. 4.

Comparison of external and internal thyroid doses at the municipality level

For each of 16 municipalities, Fig. 6 plots the ratio of median internal thyroid doses to median of external thyroid doses and the ratio of arithmetic mean of internal thyroid doses to arithmetic mean of external thyroid doses. Since the internal thyroid dose was age-dependent, the ratios estimated for two typical age categories (1-yo and 15-yo) are shown. The ratio ranged from 0.9 to 21.1 for dose of the 1-yo and from 0.56 to 13.8 for dose of the 15-yo, when comparing by median values. Internal thyroid doses for 1-yo were around 1.5 to 2 times higher than those for 15-yo, while external thyroid doses were not so age-dependent. Thus, the ratios for 15-yo were lower for each municipality.

The median ratios are shown on an ambient dose rate map [26] in Fig. 7. Generally, the ratio was larger for coastal area municipalities (see also Fig. 6). In the case of using the internal thyroid dose of 1-yo, the ratio ranged from 4.4 (Okuma Town) to 21.1 (Shinchi Town) for coastal municipalities, while it ranged from 0.91 (Date City) to 3.94 (Kawamata Town) for inland areas, except for Tamura City. Tamura City had the highest ratio (13.9) among the inland areas, but more than half of the internal thyroid dose resulted from ingestion dose in the case of 1-yo [23].

Figure 8 shows the percentages of external thyroid dose to the total thyroid dose for 1-yo and 15-yo. For the inland areas such as Date City and Iitate Village, the ratios were generally higher than those for coastal areas. The maximum percentage was 64% for Date City among the 15-yo. Figure 9 shows a geographical distribution of the percentages for 15-yo, which indicated that external thyroid dose was not a negligible level, especially for inland areas northwest of the FDNPP site.

Comparison between the ratios for individual and municipality levels

The ratios of internal thyroid dose to external thyroid dose were compared for the four municipalities where both individual and municipality level comparisons were made. The comparisons are shown in Table 2. The average ages of selected individuals for four municipalities (Nos 1 and 2 in Table 2) were almost the same (9.0 to 9.9 y), as described before. The external thyroid doses were not so age-dependent as shown in Table 1, whereas the internal thyroid doses were significantly age-dependent [23]. The ratios estimated from the individual level (Nos 1 and 2) were smaller than the ratio estimated from the municipality level using internal thyroid dose of the 1-yo (No. 3) and larger than those estimated using internal thyroid dose of the 15-yo (No. 4). Considering the age dependence of internal thyroid dose (dose of 1-yo was larger than dose of 15-yo), the results of Nos 3 and 4 (comparison at municipality level) were consistent with those of Nos1 and 2 (comparison at individual level). The comparison at the individual level was conducted only for four municipalities, considering time necessary for the calculation of individual internal thyroid doses. The above results suggested that the comparison at the municipality level conducted for 16 municipalities gave results consistent to those obtained at the individual level.

DISCUSSION

Ratios of internal thyroid dose to external thyroid dose among the municipalities

External dose is mostly caused by radionuclides deposited onto the ground [14]. Rain and snow enhance the deposition of radionuclides onto soil but do not influence inhalation dose. Resuspension of deposited radionuclides that makes a contribution to inhalation dose might possibly occur. Saito *et al.* [27] estimated the maximum deposition density of ^{131}I was 5.5 × 10^4 Bq/m^2 (as of 14 June 2011) and they estimated a conservative resuspension rate (ratio of airborne concentration by resuspension to deposition density) was 10^{-6} m^{-1}. These parameters were used to estimate the maximum airborne ^{131}I concentration by resuspension was around 140 Bq/m^3 as of 15 March 2011. This ^{131}I concentration could result in an internal thyroid dose for one day of around 0.9 mSv to 1-yo who stayed indoors, based on a calculation using dosimetric parameters adopted by Suzuki *et al.* [23]. Considering that this was the maximum dose based on conservative assumptions, the dose due to inhalation of re-suspended radioiodine would likely be insignificant in the total thyroid dose, as the UNSCEAR report described [28].

The areas where wet deposition occurred formed high ambient dose areas; these are red shaded in Fig. 7. In contrast, for areas where the radioactive plumes passed but no precipitation was observed, inhalation dose was relatively high, while external dose was relatively low. Areas along the coast in southern and northern directions from the FDNPP corresponded to these areas, where as areas in a northwestern direction experienced rain or snow when the radioactive plumes passed (Date City, Iitate Village, Kawamata Town, etc.) [29].

Thus, the ratio of internal thyroid dose to external thyroid dose was generally higher for the coastal areas. The highest ratio was found for Shinchi Town, where the ambient dose rate was relatively low, while

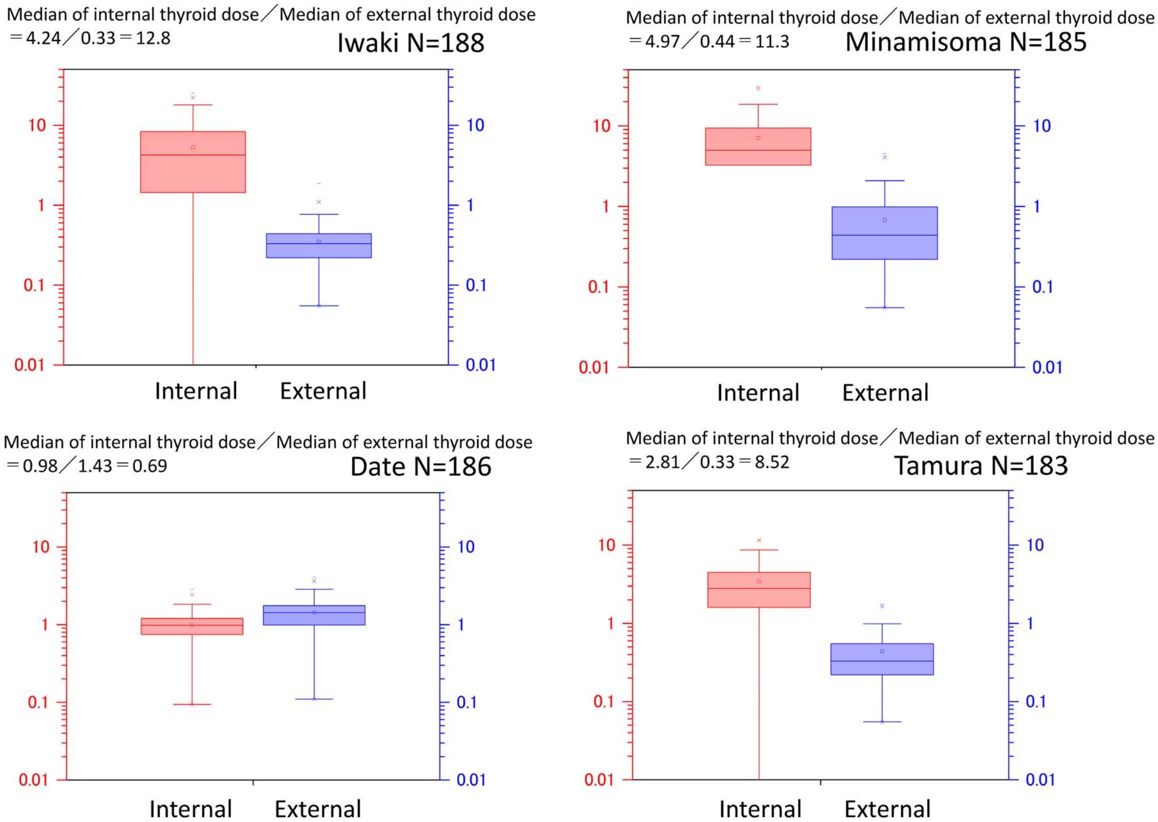

Fig. 4. Distributions of external and internal thyroid doses estimated for randomly selected individuals after the exclusion for each of four municipalities.

Table 2. Comparison of ratio of internal thyroid dose to external thyroid dose by different methods

No	Comparison methods	Reference Figure	Ratio of internal thyroid dose to external thyroid dose calculated from (A)/(B)* (see the right columns)				(A)	(B)
			Iwaki	Minamisoma	Date	Tamura		
1	Individual level	Fig. 3	12.8	11.3	0.69	8.52	Median of internal thyroid doses for selected individuals aged under 20	Median of external thyroid doses for selected individuals aged under 20
2	Individual level	Fig. 4	14.5	11.1	0.67	8.00	Internal thyroid doses for selected individuals aged under 20	External thyroid doses for selected individuals aged under 20
3	Municipality level	Fig. 5(a)	15.5	11.8	0.91	13.9	Median of internal thyroid doses of 1-yo#	Median of external thyroid doses for all individuals aged under 20
4	Municipality level	Fig. 5(b)	10.0	7.45	0.56	7.27	Median of internal thyroid doses of 15-yo#	Median of external thyroid doses for all individuals aged under 20

*For the second row, medians of (A)/(B) for the selected individuals are shown #These values were taken from [22]

the inhalation dose was higher due to repeated passages of radioactive plumes containing radioactive iodine on 12, 18, 20 and 22 March 2011 [29].

According to the analysis of the correlation between internal and external thyroid doses, the correlation coefficient (r_s) for individuals from all four cities (Fig. 3) was −0.116, although that for each of the

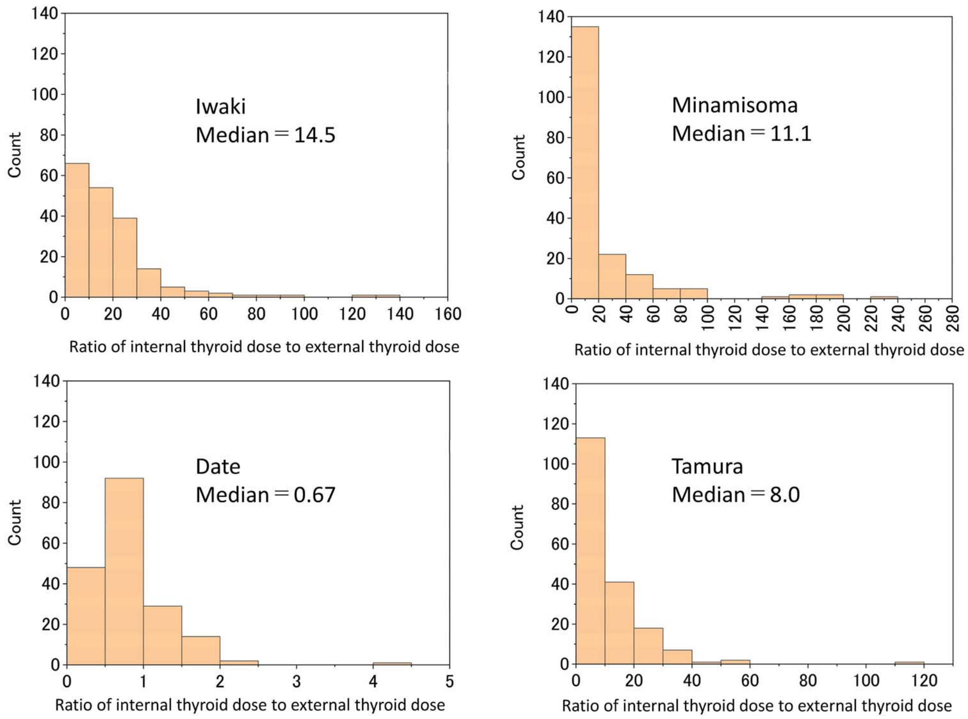

Fig. 5. Distribution of ratios of internal thyroid dose to external thyroid dose estimated individually for randomly selected subjects for each of four municipalities.

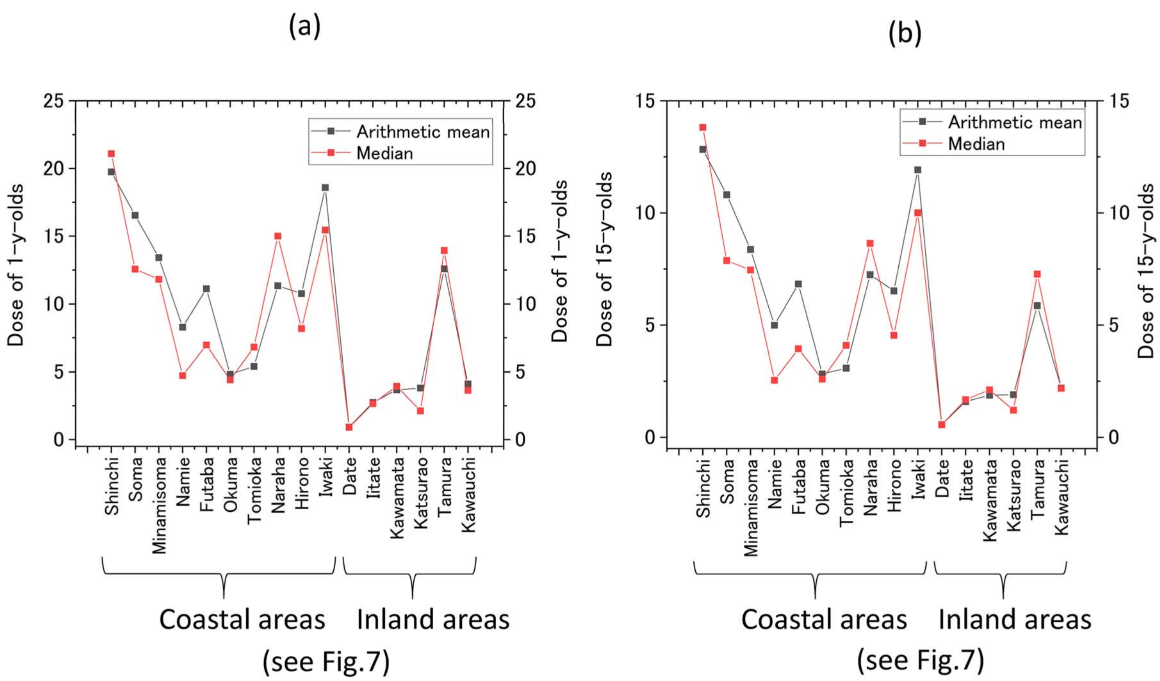

Fig. 6. The ratio of median internal thyroid doses to median of external thyroid doses and the ratio of arithmetic mean of internal thyroid doses to arithmetic mean of external thyroid doses for 16 municipalities of (a) 1-yo and (b) 15-yo. The ratios derived from arithmetic mean and median values are plotted in black and red, respectively.

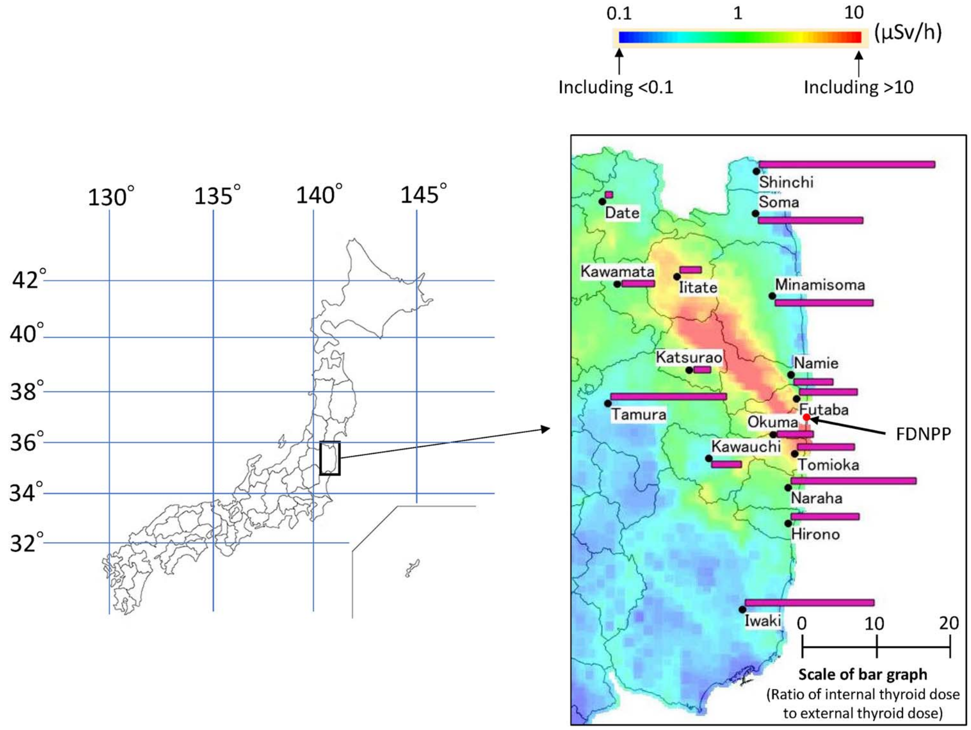

Fig. 7. Median ratios of internal thyroid dose (1-yo) to external thyroid dose plotted on an ambient dose rate map representing a geographical distribution. The rates were as of 31 May 2012 [26].

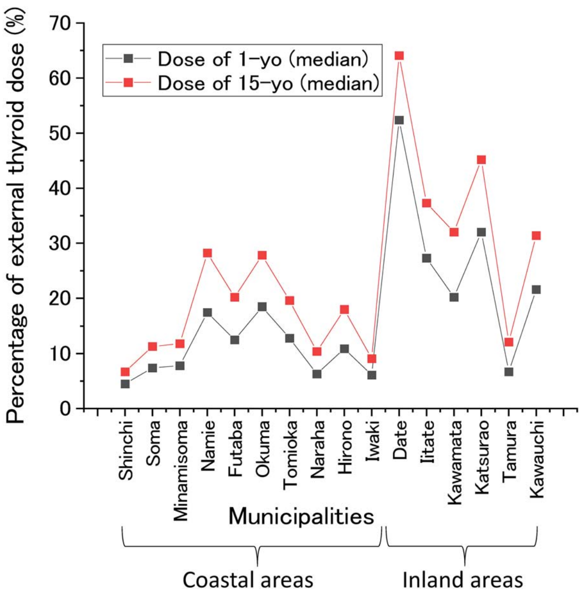

Fig. 8. Percentage of external thyroid dose to the total thyroid dose (i.e. the summed median value for external and internal thyroid doses) of 1-yo and 15-yo for each municipality.

four municipalities separately ranged from 0.204 to 0.440. In addition, the ratio of internal thyroid dose to external thyroid dose was considerably different among the 16 municipalities, as shown in Fig. 6. There was no consistent relationship between external and internal thyroid doses for the 16 municipalities. It seemed that external dose was not representative for total thyroid dose for municipalities located over a wide area, even if a weak correlation was observed for a specified municipality such as Iwaki City. Thus, the total thyroid dose approach should be used for further studies on investigating the association between radiation dose and thyroid cancer.

Percentages of external dose to total thyroid dose

The maximum percentage of external dose to total thyroid dose was about 64% for 15-yo of Date City. As shown in Figs. 8 and 9, the external thyroid dose was not negligible especially for most of the inland municipalities. Although the highest percentage among the coastal municipalities was 28.2% for Namie Town (internal thyroid dose of 15-yo) where most residents evacuated to inland municipalities [13], the ratios for the inland municipalities (Date City, Iitate Village, Kawamata Town, Katsurao Village and Kawauchi Village) exceeded 30% (Fig. 9).

In the present study, 4-month external doses estimated by the Basic Survey were used. If the dose integration period becomes longer, external doses should be larger. In terms of municipality average, the first-year dose was around two times that of the first 4-month dose [30]. On the other hand, internal thyroid exposure due to radioiodine resulting from the accident was almost no longer occurring after the first 4 months due to the short half-lives (HL) of radioiodine: ^{131}I (HL = 8.0 days), ^{132}I (HL = 2.3 hours), ^{133}I (HL = 20.8 hours) and ^{135}I (HL = 6.6 hours). Thus, if a longer dose estimation period is taken, additional internal dose will be negligible, which will lead to a higher

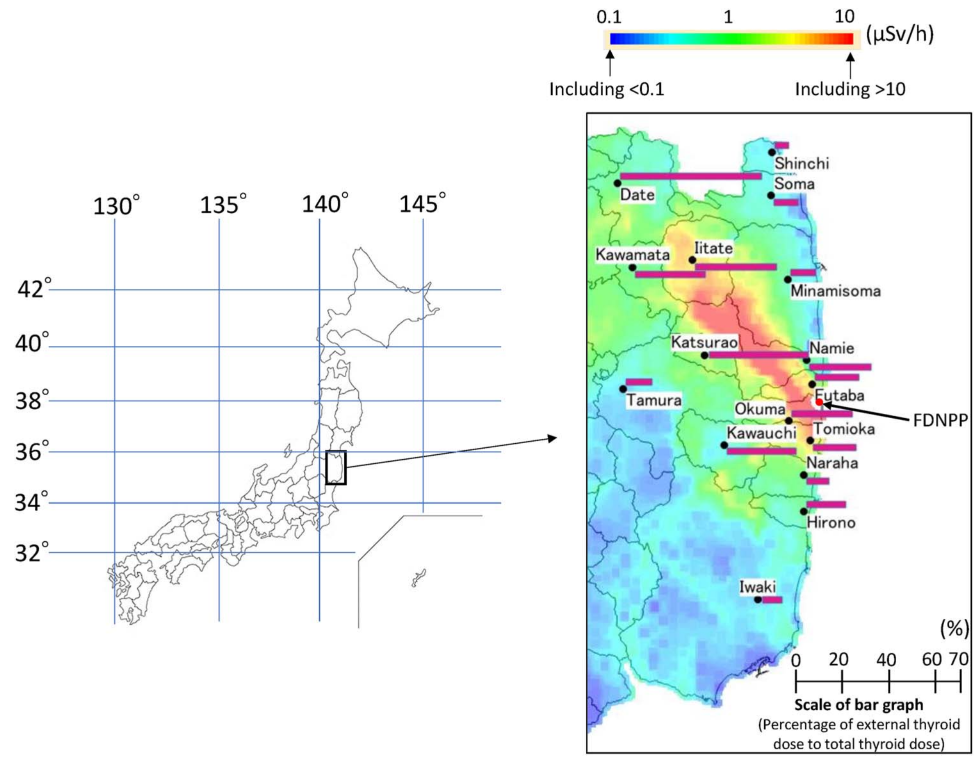

Fig. 9. The percentages shown in Fig. 8 for 15-yo plotted on an ambient dose rate map representing a geographical distribution. The rates were as of 31 May 2012 [26].

percentage of external dose to total thyroid dose. However, it is difficult to estimate individual external doses after the first 4 months due to the lack of behavior data. Using the 4-month external dose is practical for conducting a case-control study on thyroid cancer and radiation dose.

As described in the Introduction section, association between radiation and thyroid cancer was a concern among residents. It is ideal to analyze the radiation effect using reliable individual doses and sufficient numbers of thyroid cancer cases. However, the analysis needed to start with available data to respond to the residents' demand to answer the question: Is thyroid cancer associated with radiation dose or not? Thus, ambient dose rates or external doses were used for the analysis in an early stage, without knowing that those parameters had a poor correlation with total thyroid doses. Recently, methodology to estimate individual internal thyroid doses has been developed [13, 23] and the total thyroid dose was estimated in the present study using the Basic Survey data. Also, the number of thyroid cancer cases accumulates year by year. In these respects, the analysis is being improved step by step. Further future analysis will be done using the latest data on thyroid dose and thyroid cancer cases. The internal and external thyroid doses described in this article are considered to be the best estimates for individual thyroid doses to be used for analysis going forward.

Both external and internal thyroid dose estimations have uncertainties. Those of internal thyroid dose were described elsewhere [23]. For external thyroid dose, the main uncertainty resulted from the methodology for the Basic Survey (estimation of individual effective doses due to external exposure). The uncertainties for the Basic Survey were described elsewhere [18]. Regardless of these uncertainties, the main conclusion described below will be valid.

CONCLUSION

For all 16 municipalities around the FDNPP, there was no consistent relationship between external and internal thyroid doses of the residents. This suggested that external dose was not representative for total thyroid dose for municipalities located over a wide area. For most of the municipalities studied, internal thyroid doses were larger than external thyroid doses. However, especially for the inland municipalities external thyroid dose was not negligible (it was more than 30%). Thus, individual thyroid doses from both external and internal exposures should be used to analyze the association between radiation dose and thyroid cancer detection rates in persons exposed in the FDNPP accident.

SUPPLEMENTARY DATA

Supplementary data is available at *RADRES Journal* online.

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CONFLICT OF INTEREST

The authors declare they have no conflicts of interest.

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