ATTACHMENT A-2

THE ESTIMATION OF THYROID DOSES RESULTING FROM THE ACCIDENT AT THE FUKUSHIMA DAIICHI NUCLEAR POWER STATION AND THEIR VALIDATION

UNSCEAR 2020/2021 Report, annex B, Levels and effects of radiation exposure
due to the accident at the Fukushima Daiichi Nuclear Power Station: implications
of information published since the UNSCEAR 2013 Report

Contents

This attachment describes the models and approaches the Committee has used to estimate the intake of radioiodine by inhalation and ingestion following the accident at the Fukushima Daiichi Nuclear Power Station (FDNPS) and how these intakes have been transformed to effective dose and absorbed dose to various organs. A dosimetric model specific to the Japanese population, that has an iodine-rich diet, has been developed for the latter purpose. The Committee has also undertaken an independent assessment of thyroid doses based on measurements of dose rates near the neck for more than 1,000 people in several municipalities of Fukushima Prefecture made in March–April 2011 and compared them with those estimated by Japanese scientists. Finally, the Committee has compared its modelled estimates of thyroid dose with those derived from measurements of the thyroid in order to validate the models used.

Notes

For consistency, doses in this attachment are quoted, in general, to 2 significant figures. This should not be interpreted as an indication of their precision that is often much less.

This attachment has not been formally edited.

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I. INTRODUCTION

1. This attachment summarizes the approaches and models used by the Committee, in its UNSCEAR 2013 Report [UNSCEAR, 2014], to estimate doses to the population of Japan resulting from intakes of radioiodine following the accident at FDNPS. Data and information that have since been published, or made available to the Committee, are summarized, in particular where these have the potential to improve the validity of the estimated doses and/or reduce their uncertainty. The Committee has used this new information to adapt the approaches and models it had used in the UNSCEAR 2013 Report to estimate doses and the more significant changes are described including improvements in the estimation of airborne concentrations of radionuclides, more realistic estimates of the amount of radioiodine ingested and in the development and use of a Japanese-specific biokinetic model for the intake of radioiodine.

2. The Committee has also undertaken an independent assessment of thyroid doses based on measurements of dose rates near the neck for more than 1,000 people in several municipalities of Fukushima Prefecture made in March–April 2011 and compared them with those estimated by Japanese scientists. The results of this comparison are summarized below. Finally, the Committee has compared its modelled estimates of thyroid dose with those derived from measurements of the thyroid with the aim of validating the models and approaches used.

3. The Committee has focused on estimating doses for four groups of geographical areas of Japan: Group 1 included municipalities in Fukushima Prefecture from which some or all of the population were evacuated in the days to months after the accident; Group 2 included municipalities and parts of municipalities of Fukushima Prefecture that were not evacuated; Group 3 included selected prefectures in eastern Japan that were neighbouring Fukushima Prefecture (Ibaraki, Miyagi, Tochigi and Yamagata prefectures); Group 4 included all the remaining prefectures of Japan.

4. Within these groups, the Committee has assessed doses for the three standard International Commission on Radiological Protection (ICRP) age groups as of 2011 (1-year-old infants, 10-year-old children and adults).

II. THYROID DOSE ASSESSMENT IN THE UNSCEAR 2013 REPORT

5. Assessment of doses from the intake of radioiodine into the body took account of intakes via inhalation and ingestion of food and drinking water. The former was based on the source term assumed in the UNSCEAR 2013 Report and an atmospheric transport, dispersion and deposition model (ATDM) of radioiodine in particulate and gaseous forms; and the latter was based on numerous radiation measurements of food products in a database compiled by the Food and Agriculture Organization (FAO) and the International Atomic Energy Agency (IAEA) in collaboration with the Ministry of Agriculture, Forestry and Fisheries (MAFF) and the Ministry of Health, Labour and Welfare (MHLW) in March–May 2011 [UNSCEAR, 2014].

6. Two methods were used to estimate doses from the intake of radioiodine by inhalation. The first was based on ATDM modelling of the time-dependent concentrations in air of ^{131}I, ^{132}I, ^{133}I and ^{132}Te available on a 5 × 5 km uniform grid covering Japan. While these concentrations were derived using the then best available source term and ATDM models, there were significant uncertainties in their values at specific locations and times. This approach was used to estimate doses for people from evacuated municipalities of Fukushima Prefecture.

7. The second was based on the estimated time-integrated concentrations of radioiodine in air derived from measured ground deposition levels and the aggregated deposition velocity derived from ATDM. The aggregated deposition velocities were based on ratios of ATDM estimates of the time-integrated concentrations or radioiodine in air versus measured ground deposition concentrations. This approach was applied to people in non-evacuated municipalities of Fukushima Prefecture and the rest of Japan.

8. The Committee used standard values of the age-dependent breathing rates and dose coefficients for organ doses and for effective dose [ICRP, 1994; ICRP, 2012]. These dose coefficients were based on a default particle size of 1 µm. The inhalation rates applied were the average rates over a day from the ICRP model of the respiratory tract. No allowance was made for any possible reduction in concentrations of radioiodine in air indoors compared with those outdoors.

9. Doses from ingestion were based on measurements of concentrations of radioiodine in food compiled under the guidance of FAO and IAEA in collaboration with MAFF and MHLW. The measured concentrations were combined with information on the amounts of particular foods people ate to obtain estimated doses.

10. Within Japan, extensive measurements were made of the concentrations of radionuclides in different foods (terrestrial and aquatic) starting in parts of Fukushima Prefecture a few days after the accident. These measurements were mainly intended to identify where restrictions on food supplies were required rather than to assess the doses to different population groups. The measurement data used were for foods as marketed, not as consumed (e.g., after culinary preparation, etc.). Many of the measurements were at or below the limits of detection and in these cases, it was generally assumed that the concentrations of ^{131}I was 10 Bq/kg in each type of food, the minimum detection level. In view of the short half-life of ^{131}I (8.02 days), all concentrations in food for this radionuclide were assumed to be zero beyond four months after the accident.

11. There were insufficient data in the first months after the accident to adopt a fine spatial resolution for the assessment of the doses from ingestion of radionuclides. It was assumed that the majority of people in Japan obtained their food from supermarkets where food is sourced from the whole of the country.

12. The ICRP dose coefficients applied in the 2013 Committee's study [ICRP, 1993; ICRP, 1995] were based on generic anatomical and physiological human data and, as such, were unlikely to have been entirely appropriate for assessing doses to the thyroid of Japanese people because of the high iodine content of a typical Japanese diet.

III. NEW DATA AND INFORMATION AVAILABLE SINCE 2013

A. Thyroid measurements

13. Measurements of radioiodine in people's thyroids provide a direct source of information on their exposure. In March–April 2011, measurements of different quality and informativeness were made of gamma-radiation emitted from thyroids of: *(a)* permanent residents of, and evacuees from municipalities in Fukushima Prefecture; *(b)* embassy personnel in Tokyo City [Uyba et al., 2018]; and *(c)* the United States Department of Defense (DoD) and the United States Department of Energy (DOE) personnel located in Japan [DTRA, 2012; DTRA, 2013a; DTRA, 2014].

14. In total more than 1,500 measurements of people of various age and both sexes, were carried out by several groups of Japanese and, to a lesser extent, foreign experts. The larger measurement campaign was conducted over the period 26 to 30 March 2011 in Iitate Village, Iwaki City and Kawamata Town by the Support Team for Residents Affected by Nuclear Incidents [Hosokawa et al., 2013; Kim et al., 2012; Kim et al., 2020]. In total, measurements of dose rate at the thyroid gland were made on 1,080 children aged 1 to 15 years using handheld dose-rate instruments. According to Hosokawa et al. [Hosokawa et al., 2013], the measurements were performed using NaI(Tl) scintillator (1 × 1 inch) survey meters. Original calibration of this equipment was done before the FDNPS accident and was specified, retrospectively, in Kim et al. [Kim et al., 2020]. Measured dose rates were low, in most cases lower than the background level. Personal interviews with those measured were not conducted.

15. Tokonami et al. reported the results of thyroid monitoring made during 12–16 April 2011 on 62 evacuees aged from 0 to 83 years from the Tsushima area of Namie Town and the coastal area of Minamisoma City [Tokonami et al., 2012]. They detected ^{131}I in 46 people with a 3 × 3 inch NaI(Tl) scintillation spectrometer.

16. The concentration of radioiodine in evacuees and short-term visitors to Fukushima Prefecture was measured by a whole-body counter at the Nagasaki University on 15 March 2011 [Matsuda et al., 2013]. A horizontal bed-type scanner equipped with two NaI(Tl) scintillation detectors in the upper and the lower position was used for 173 people who stayed in the Fukushima Prefecture between 11 March and 10 April 2011. Calibration of the counting efficiency and energy resolution was performed using a bottle manikin absorption (BOMAB) phantom. The minimum detection level for ^{131}I was 30 Bq. Iodine-131 was detected in 55 individuals. More information is available for 49 individuals with ^{131}I detected in a series of measurements with the same whole-body counter at Nagasaki University [Morita et al., 2013].

17. A group of experts from the Federal Medical Biological Agency of the Russian Federation conducted, in April 2011 at the Russian Embassy in Japan, spectrometric measurements of 268 staff members and their families, including a few children, living in Tokyo and its suburbs [Uyba et al., 2018]. Thyroid measurements were conducted with a mobile scintillation spectrometer. The measurement duration was two minutes, and the minimum detection level was 100 Bq of ^{131}I in an adult thyroid. Of those measured, three adults exceeded the minimum detection level with up to 130 Bq of ^{131}I in their thyroids. Each measurement was accompanied by a personal interview focused on their residence history and dietary habits.

18. Measurements were made, inter alia, of the thyroids of 8,238 DoD and DOE personnel (and/or their family members) who were based in Japan or nearby at the time of the accident, or on-board ships in the general vicinity [DTRA, 2012; DTRA, 2014]. Of these, 238 individuals had measured levels (i.e., above minimum detection levels) of radioiodine in their thyroids. Nine hundred and forty-four people were measured using fixed scanners at naval bases on the west coast of the United States of America and, of these, 104 had measured concentrations of ^{131}I in their thyroids in the range of 37 to 296 Bq. The average absorbed dose to the thyroid for the 238 individuals with measured levels of radioiodine in the thyroid was about 0.7 mGy [DTRA, 2013b]. Deterministic and probabilistic assessments [DTRA, 2012; DTRA, 2013a] have been made of doses from intakes of radionuclides, with the former being deliberately conservative.

19. The Committee has also made use, to varying extents, of results of thyroid measurement published in the peer-reviewed literature for model validation and further elaboration.

B. Ingestion of radioiodine

20. Murakami and Oki have undertaken a comprehensive assessment of the ingestion of radionuclides during the first year after the FDNPS accident by people of various ages residing in the cities of Fukushima, Osaka and Tokyo [Murakami and Oki, 2014]. They used data from national food monitoring. Food and drinking water were classified into 18 categories, which included rice and other cereals, vegetables and fruits, dairy and meat products, fish, etc. The consumption rates of food and water by people of different sex and age were taken from national statistics. In contrast to analyses made by international organizations [UNSCEAR, 2014; WHO, 2012], Murakami and Oki carefully considered the particularities of regional trade in Japan and the effects of countermeasures. For Fukushima City, two cases were considered: Case 1 – purchase of all products on the market; and Case 2 – consumption of locally produced vegetables (e.g., by agricultural workers comprising about 4% of the population) and purchase of other products on the markets. By modelling, the authors found reasonable agreement with measurements of radiocaesium in diet; similar validation for radioiodine was not/could not be performed.

21. The doses decreased significantly (see table A-2.1) with increasing distance from FDNPS: Fukushima > Tokyo > Osaka. The thyroid dose for children is about three times higher than that for adults, mainly due to the consumption of drinking water and liquid foods (milk, etc.). For residents of Fukushima Prefecture who were assumed to have consumed local vegetables (agricultural workers comprising about 5% of the population), the average dose was about three times higher than that of other residents. In general, according to Murakami and Oki's estimates, the dose from ingestion of ^{131}I in food and drinking water was an order of magnitude lower than that estimated by the Committee [UNSCEAR, 2014; WHO, 2012].

Table A-2.1. Estimated doses to adults and children of various ages living in different locations, from the ingestion of ^{131}I in food and drinking water in the first year ([Murakami and Oki, 2014], International Commission on Radiological Protection dose coefficients)

Location	*Absorbed dose to thyroid [a] (mGy)*			*Effective dose [a] (mSv)*		
	Adults	*7–12 years old*	*1–6 years old*	*Adults*	*7–12 years old*	*1–6 years old*
Fukushima City (market)	0.82	2.1	2.6	0.034	0.090	0.11
Fukushima City (locally grown vegetables)	2.6	5.8	6.9	0.11	0.24	0.28
Tokyo City	0.22	0.38	0.49	0.009	0.016	0.020
Osaka City	0.016	0.032	0.040	0.001	0.001	0.002

[a] The doses reported by Murakami and Oki were estimated using generally applicable dose coefficients for the intake of radioiodine recommended by ICRP; they would decrease by a factor of about two had Japanese-specific dose coefficients been used (see section IV).

IV. JAPAN-SPECIFIC DOSE COEFFICIENTS FOR INTAKE OF RADIOIODINE

A. Stable dietary intake of iodine in Japanese diet

22. The Japanese population has an iodine-rich diet [Katagiri et al., 2015; Leggett, 2010; Nagataki et al., 1967; Zimmermann et al., 2004; Zimmermann et al., 2005]. Stable iodine comes mainly from seafood, particularly algae, which is a traditional component of the Japanese diet. Typically, kelp contributes up to 90% of the total iodine intake in Japan [Katagiri et al., 2015]. In the review of Zava and Zava [Zava and Zava, 2011] the average Japanese iodine intake was

estimated to be about 1,000–3,000 μg/d, which may result in suppression of iodine accumulation by the thyroid gland. Tables A-2.2 and A-2.3 summarize Japan-specific data on the dietary iodine intake rate, Y (μg/d), and decay-corrected percentage thyroid uptake U(%), of ingested iodine at 24 hours. The reference ICRP biokinetic model [ICRP, 1989] assumes a moderate level of dietary intake of stable iodine at about 200 μg/d for adults [ICRP, 1975].

Table A-2.2. Dietary intake rate, Y, of stable iodine (range, mean and standard deviation) and fractional thyroid uptake U[a] (range and mean) measured in residents of Japan

Number of individuals	*Y range (μg/d)*	*Y mean (μg/d)*	*Y_{SD} (μg/d)*	*U range (%)*	*U mean (%)*	*Reference*
4 adults	878–1 690	1 132	n/a	10.2–15.8	12.5	[Nagataki et al., 1967]
7 adults	n/a	1 523	356	9.5–26.6	16.7	[Ohtaki et al., 1967]
2 adults	13 760–17 300	15 540	n/a	2.6–7.5	5.1	[Nagataki et al., 1967]
302 6–12-year-old children Central Hokkaido	≈50–14 000[b]	≈300[b]	n/a	n/a	n/a	[Zimmermann et al., 2005]
280 6–12-year-old children Coastal Hokkaido	≈40–11 000[b]	≈700[b]	n/a	n/a	n/a	[Zimmermann et al., 2005]
54 adults	≈40–8 700	≈1 000	≈2 000	n/a	n/a	[IAEA, 2008]
390 adults	See table A-2.3					[Katagiri et al., 2015]
Not specified					12.8 ± 5.7	[Kunii et al., 2012]
15 adults	n/a	n/a	n/a	9.1–26	16.1	[Kusuhara and Maeda, 2017]

[a] Decay-corrected fractional thyroid uptake, U, of ingested radioiodine at 24 hours.
[b] Estimated from concentrations of stable iodine in urine in an assumption of the urinary excretion rate of about 1 L/d.

Table A-2.3. Intake rate of stable iodine in the various diets of Japanese adults [Katagiri et al., 2015]

Iodine intake, Y	*Percentage of men (number)*			*Percentage of women (number)*		
	Cluster I Rice and vegetables (n=101)	*Cluster II Meat, non-Japanese noodles and sugar-sweetened beverages (n=34)*	*Cluster III Fish, Japanese noodles and alcohol (n=60)*	*Cluster I Rice and vegetables (n=22)*	*Cluster II Fish and Japanese noodles (n=33)*	*Cluster III Bread and non-Japanese noodles (n=140)*
<95 μg/d	5.9 (6)	23.5 (8)	1.7 (1)	13.6 (3)	6.1 (2)	18.6 (26)
>3 000 μg/d	22.8 (23)	5.9 (2)	18.3 (11)	50.0 (11)	36.4 (12)	13.6 (19)

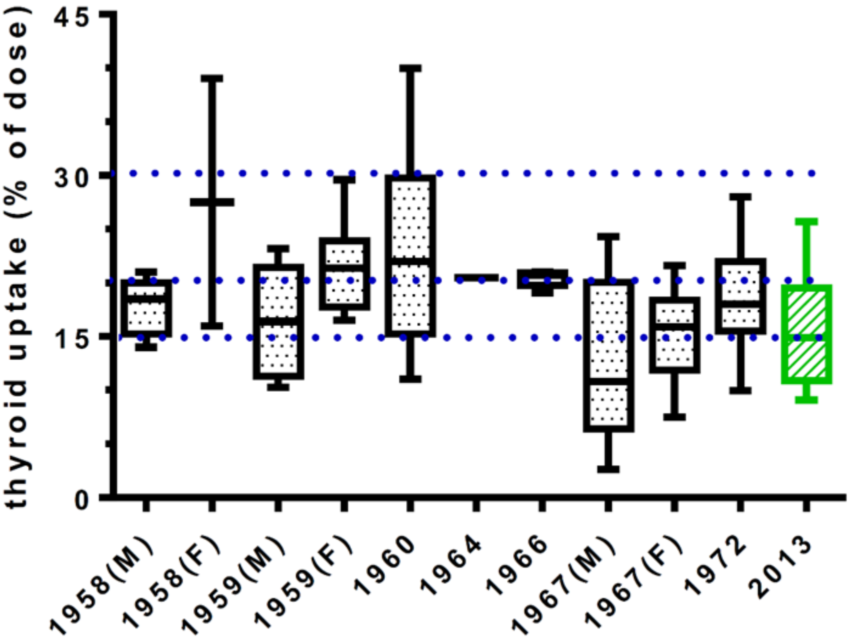
23. Generally, the intake rate of stable iodine for Japanese people is substantially higher than in countries with a Western pattern diet [ICRP, 1975]. A significant inter-individual and interregional variability of the dietary iodine intake is also observed in Japan. For some Japanese people, a low iodine intake can be associated with the Western pattern diet.

B. Thyroid uptake in the Japanese population

24. Some values of the decay-corrected percentage thyroid uptake, U(%), of ingested radioiodine at 24 hours are given in table A-2.2. Figure A-2.I from Kusuhara and Maeda [Kusuhara and Maeda, 2017] summarizes the results of Japanese studies conducted during 1958–2013. All recent data demonstrate that U-values in Japan are typically lower than the reference ICRP value of 30%. In a recent study, Kusuhara and Maeda [Kusuhara and Maeda, 2017]

obtained a mean U = 16.1 ± 5.4% for 15 Japanese euthyroid male subjects from Nagasaki, and a similar study in Tokyo resulted in the value of U = 12.8 ± 5.7% [Kunii et al., 2012].

Figure A-2.I. Fractional thyroid uptake, U(%), of radioiodine by Japanese adults [Kusuhara and Maeda, 2017]



C. International Commission on Radiological Protection dose coefficients for intake of radioiodine

25. In the UNSCEAR 2013 Report, the Committee estimated doses to the thyroid gland based on ICRP reference dose coefficients [ICRP, 1993; ICRP, 1995]. These age-dependent dose coefficients were derived by ICRP with the use of a reference 3-compartmental iodine biokinetic model [ICRP, 1989; ICRP, 1993].

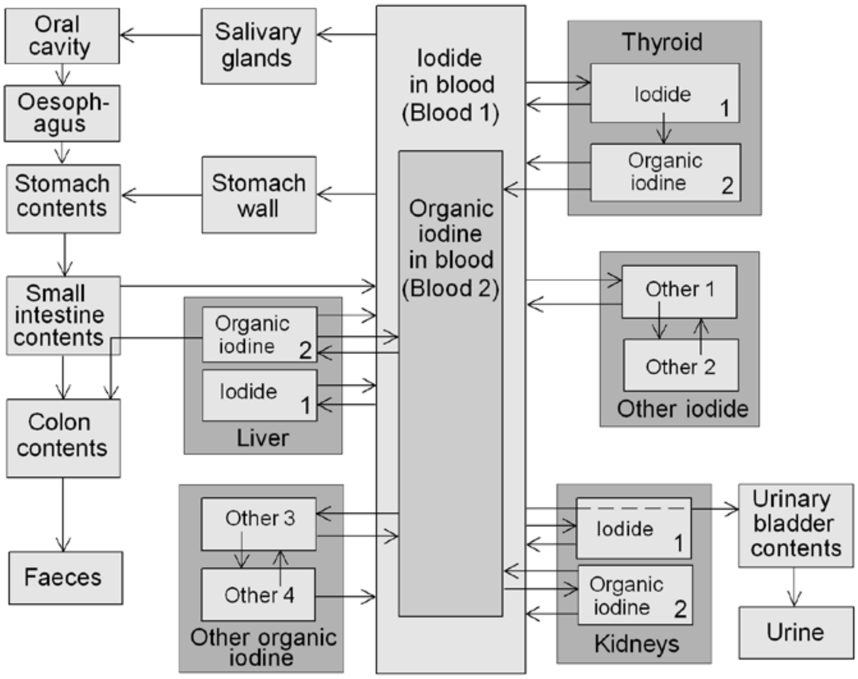
26. The ICRP reference biokinetic and dosimetric models, and the associated set of reference dose coefficients, were primarily intended for applications in routine radiation protection, such as optimization of protection and demonstration of compliance. For these reasons, the parameter values of ICRP reference models are generalized and based on worldwide-average data. The reference ICRP dose coefficients for internal exposure are expressed in terms of protection quantities, i.e., committed effective dose and committed equivalent doses to organs or tissues of the ICRP Reference Person [ICRP, 2001].

27. The simplified model structure and fixed value of 24-hour fractional thyroid uptake of U = 30% (related to the reference dietary intake of stable iodine at the level of about 150 µg/d) results in unrealistic dose estimates for situations where the actual dietary intake of iodine is substantially lower or higher than the reference level.

28. In 2017, ICRP adopted a new model of iodine biokinetics in adults [ICRP, 2017] that is based on the model of Leggett [Leggett, 2010]. The model, similar to the model of Berkovski [Berkovski, 2002], provides an improved description of the short-term biokinetic processes and permits more precise assessments of exposure to short-lived isotopes of iodine, namely ^{132}I, ^{133}I

and exposure to ^{132}Te that has a radioactive progeny ^{132}I. The structure of the model is presented in figure A-2.II, and its reference parameter values for workers are given in the ICRP Publication 137 [ICRP, 2017]. The new age-dependent version of the model is under development [ICRP, 2020].

Figure A-2.II. The structure of the new International Commission on Radiological Protection iodine biokinetic model for adults [ICRP, 2017]



D. Japan-specific indicative dose coefficients for intakes of radioiodine

29. The default parameter values of the model [Leggett, 2010] are based on the following values for dietary intake of stable iodine: 130 µg/d for an adult female, 190 µg/d for an adult male, and 160 µg/d as a reference sex-averaged value. However, the key advantage of the model is its capability to account for a non-reference level of dietary intake of stable iodine. The thyroid responds to changes in the level of dietary stable iodine intake by modification of its rate of iodide uptake from blood plasma. The detailed description of the regulation of the thyroid uptake and secretion of thyroid hormones is given elsewhere [Luster et al., 2019] whereas the paper [Leggett, 2010] includes guideline and parameter values for simulation of the influence of elevated levels of stable iodine in the diet. Age-specific data demonstrate that there is no pronounced dependence of the fractional thyroid uptake U with age [Fields et al., 1957; ICRP, 2020].

30. The Committee developed the new model to derive population-specific indicative dose coefficients for various types of Japanese diet with different content of stable iodine that determines the fractional thyroid uptake, U. The values of the indicative dose coefficients "dose per exposure (time-integrated air concentration)", specifically "organ absorbed dose per exposure, Gy per (Bq s/m^3)" and "effective dose per exposure, Sv per (Bq s/m^3)" were calculated for inhalation of various physico-chemical forms of ^{131}I, ^{132}I, ^{133}I and ^{132}Te and three types of the diet: typical Japanese diet (U = 15%), kelp-rich diet (U = 5%), and a Western pattern diet (with a reference value of U of about 30%) that is popular among some groups of the Japanese population. The dose coefficients were developed for the thyroid, red bone marrow, female

breast and colon as well as for effective dose from inhalation of aerosols, Type F, activity median aerodynamic diameter (AMAD) = 1 µm, methyl iodide and elemental iodine.

31. The indicative dose coefficients are provided for a non-lactating adult female, adult male, 10-year-old child and 1-year-old infant.

32. Additionally, the dose coefficients for in utero exposure are given for acute inhalation and ingestion at the 35th week of pregnancy in terms of the fetus absorbed dose and fetus effective dose per maternal exposure. These can be considered as the upper bounds of thyroid dose to the fetus for maternal intake of radioiodine by inhalation or ingestion (i.e., intakes at other times during pregnancy would result in lower dose coefficients). For intakes at other times during pregnancy, in utero doses can be estimated using the model and data of ICRP [ICRP, 2001].

33. The model in ICRP Publication 88 takes account of the fetal thyroid gland not substantially concentrating iodine prior to the 10th week of pregnancy. The ratios of the dose coefficients for inhalation or ingestion of ^{131}I at the 10th, 15th and 25th weeks of pregnancy to that for intake at the 35th week are 0.003, 0.22 and 0.62, respectively [ICRP, 2001]. Based on linear interpolation, the average dose to the thyroid gland of fetuses between the 10th and 40th weeks of pregnancy at the time of the accident (i.e., those born between mid-March and mid-October 2011) from the intake of ^{131}I is 0.47 times the dose estimated for intake by a child in utero at the 35th week of pregnancy.

34. Calculations were performed with the IDSS computer code [Berkovski et al., 1998; Berkovski et al., 2007]: this implements the biokinetic models described above, the ICRP dosimetric models [ICRP, 1989; ICRP, 1994; ICRP, 2001], and uses ICRP reference masses of target organs and tissues [ICRP, 2002] (see table A-2.4) and the definition of effective dose in ICRP Publication 103 [ICRP, 2007].

Table A-2.4. Mass of the thyroid gland used in calculations of Japan-specific indicative dose coefficients [ICRP, 2002]

Age	*1-year-old infant*	*10-year-old child*	*Adult*	
Sex	*Both*	*Both*	*M*	*F*
Thyroid mass (g)	1.8	7.9	20	17

35. The inter-individual variability of dietary habits, biokinetics, anatomy and organ masses results in a considerable variation of individual-specific doses among people of the same age and sex. Therefore, the Japan-specific dose coefficients should be regarded as indicators of the level of dose per exposure among people with differing types of diet, rather than exact values that can be attributed to a specific age, sex and diet.

36. Japan-specific indicative dose coefficients are presented in attachment A-4 for intake by adults (male and female), 10-year-old children, 1-year-old infants for various levels of dietary intake of stable iodine, and for those in utero at the 35th week of pregnancy. The dose coefficients were developed both for inhalation and ingestion of radioiodine. For inhalation, dose coefficients for intake of ^{131}I, ^{132}I, ^{133}I and ^{132}Te in various physical and chemical forms (aerosol with AMAD 1 µm, Type F, elemental iodine and methyl iodide) are given for absorbed doses per unit exposure in various organs (thyroid, bone marrow, colon and breast), Gy per (Bq s/m^3), and effective dose per unit exposure, Sv per (Bq s/m^3). For ingestion, dose coefficients are given for intake of ^{131}I in a soluble form for absorbed doses in various organs and effective dose.

37. In summary, the Japan-specific dose coefficients used by the Committee for intake of ^{131}I in various physical and chemical forms are lower by factors in the range of 1.8 to 2.3 than those recommended by ICRP for generic use worldwide [ICRP, 1993; ICRP, 1995]; the reduction varies with age at exposure, sex and diet.

V. THYROID DOSES FROM INHALATION OF RADIOIODINE

38. The Committee has estimated doses to the population of Japan from inhalation of radioiodine based on an assumed source term and models to describe how released material is dispersed in, and deposited from, the atmosphere (see attachments A-9 and A-10). The 5%, mean and 95% thyroid doses from inhalation of radioiodine and other radionuclides by adults and children, aged 10 and 1, are presented in attachment A-18 for evacuees from municipalities wholly or partially evacuated in Fukushima Prefecture (Group 1), and in attachment A-14 for residents of each of the municipalities or parts of municipalities in Fukushima Prefecture that were not evacuated (Group 2), for four neighbouring prefectures (Group 3) and for the remaining prefectures (Group 4). Estimates are also given in attachments A-14 and A-18 of average doses to the fetal thyroid for fetus in utero between the 10th and 40th weeks of pregnancy at the time of the accident (i.e., those born in the 30 weeks following the accident).

39. The inhalation doses varied widely within Fukushima Prefecture and beyond and were influenced, inter alia, by the prevailing meteorological conditions that determined where and how the released material was dispersed.

VI. THYROID DOSES FROM INGESTION OF RADIOIODINE

40. The Committee has based its estimates of doses from ingestion of radioiodine on the study undertaken by Murakami and Oki [Murakami and Oki, 2014] that took account of monitored levels of radioiodine in food and drinking water, food supply and distribution practices, losses in food preparation and countermeasures. Murakami and Oki estimated doses for three cities: Fukushima City, Osaka City and Tokyo City (or Metropolitan Area). The Committee has assumed that the ingestion doses estimated by Murakami and Oki for Fukushima City are applicable to the whole of Fukushima Prefecture; this was judged to be a reasonable approximation given food supply and distribution practices in Japan.

41. The Committee’s estimates of thyroid and effective doses are summarized in table A-2.5 for Fukushima Prefecture and other prefectures. The tabulated doses differ from those reported by Murakami and Oki because account has been taken of Japan-specific dose coefficients for the ingestion of radioiodine that are more appropriate for people with a typical Japanese diet (see section IV of this attachment); the use of Japanese-specific dose coefficients resulted in the reduction of the doses reported by Murakami and Oki by a factor of about two. The doses in table A-2.5 are more than an order of magnitude lower than the Committee’s estimates in its UNSCEAR 2013 Report. The most likely causes of the overestimate were twofold; firstly, the use by the Committee of a database compiled by FAO and IAEA [UNSCEAR, 2014] of monitored levels in food that may have been biased towards identifying samples whose levels may have exceeded limits imposed by the Japanese authorities; and, secondly, the attribution of the minimum detection level of 10 Bq/kg of ^{131}I to all samples with measurements beneath that level.

42. The Committee estimated thyroid and effective doses in other prefectures using largely the same approach as it used in the UNSCEAR 2013 Report [UNSCEAR, 2014]. The doses were estimated from monitored levels of radioiodine in food sampled in markets across the whole of

Japan (i.e., the database compiled by FAO and IAEA). The dose in a given prefecture was derived from that in Fukushima Prefecture by scaling the ratio of the monitored levels of radioiodine in food in that prefecture relative to that in Fukushima Prefecture; the ratios for Group 3 and Group 4 prefectures were 0.27 and 0.075, respectively. Notwithstanding the reservations expressed above regarding the use of the database compiled by FAO and IAEA for estimating absolute values of dose from intake by ingestion, the Committee has judged that the relative levels in (or ratios between) each prefecture should be robust.

Table A-2.5. Estimated thyroid and effective doses to adults, children and infants, living in different locations, from the ingestion of ^{131}I in food and drinking water in the first year (based on reference [Murakami and Oki, 2014] but using Japan-specific dose coefficients)

Prefecture group	*Location*	*Absorbed dose to thyroid [a] (mGy)*			*Effective dose [a] (mSv)*		
		Adults	*10-year old*	*1-year old*	*Adults*	*10-year old*	*1-year old*
2	Fukushima Prefecture	0.41	0.94	1.14	0.017	0.039	0.047
3	Neighbouring prefectures	0.11	0.25	0.31	0.005	0.010	0.013
4	Distant prefectures	0.031	0.071	0.086	0.001	0.003	0.004

[a] Estimates are not tabulated for doses to the fetus. Conservative estimates of fetal effective and thyroid doses would be factors of about 2.3 and 1.8 times greater, respectively, than the corresponding tabulated adult doses.

43. The Committee, in applying the Japan-specific dose coefficients, has taken the doses from table A-2.1 for the 7–12-year age group and assigned them to a 10-year-old child and, similarly, assigned doses for the 1–6-year age group to a 1-year-old infant. In the latter case, the doses to the 1-year-old infant may have been underestimated by up to a few tens of per cent as a result of significant variation in the thyroid dose coefficient at very young ages.

44. Based on Murakami and Oki [Murakami and Oki, 2014] and expert judgement, the confidence intervals (5–95%) for the thyroid and effective doses in table A-2.5 have been estimated to be 0.3 and 3.0 times the doses tabulated.

45. Absorbed doses in red bone marrow, breast and colon from ingestion of ^{131}I have been assessed (see table A-2.6) from the thyroid doses by the ratio of dose coefficient for a particular organ to that for the thyroid for each age, see attachment A-4.

46. Estimates have also been made by the Committee of average doses to the fetus of children in utero between the 10th and 40th weeks of pregnancy at the time of the accident (i.e., those born in the 30 weeks following the accident) and can be found in attachments A-14 and A-18.

Table A-2.6. Ratio of dose coefficients to that for the thyroid for ingestion of ^{131}I

Age	*Ratio of dose coefficients (unitless)*				
	Effective	*Thyroid*	*Red bone marrow*	*Breast*	*Colon*
1 year	0.040	1.00	3.0E-4	1.6E-4	2.3E-4
10 years	0.041	1.00	3.5E-4	1.7E-4	2.6E-4
Adult male	0.041	1.00	6.5E-4	2.3E-4	3.2E-4
Adult female		1.00	6.5E-4	3.7E-4	2.7E-4

VII. THYROID DOSES BASED ON MEASUREMENTS OF ^{131}I IN THYROIDS

A. Study population

47. The study population comprised in total 1,146 Japanese individuals:

- 1,080 individuals aged up to 15 years who were measured for radioiodine in the thyroid gland from 26 March 2011 through 30 March 2011 in three municipalities in Fukushima Prefecture: Iitate Village, Iwaki City and Kawamata Town [Kim et al., 2020];
- 3 adults in Tokai Village [Kurihara et al., 2016];
- 1 adult from Tamura [Uchiyama et al., 2015];
- 45 individuals from Minamisoma City and 17 from Namie Town [Tokonami et al., 2012].

48. The measurements of thyroids in personnel of the Russian Embassy in Tokyo [Uyba et al., 2018] were not included in the study population owing to the very small number of measurements that were above the minimum detection level (3 out of 168). The measurements of thyroids of DoD and DOE personnel were not included in the study because the focus was on exposures in the Japanese population.

B. Information available for the dose calculations

49. Table A-2.7 summarizes the availability of information that should be used in calculating absorbed doses in the thyroids of those measured.

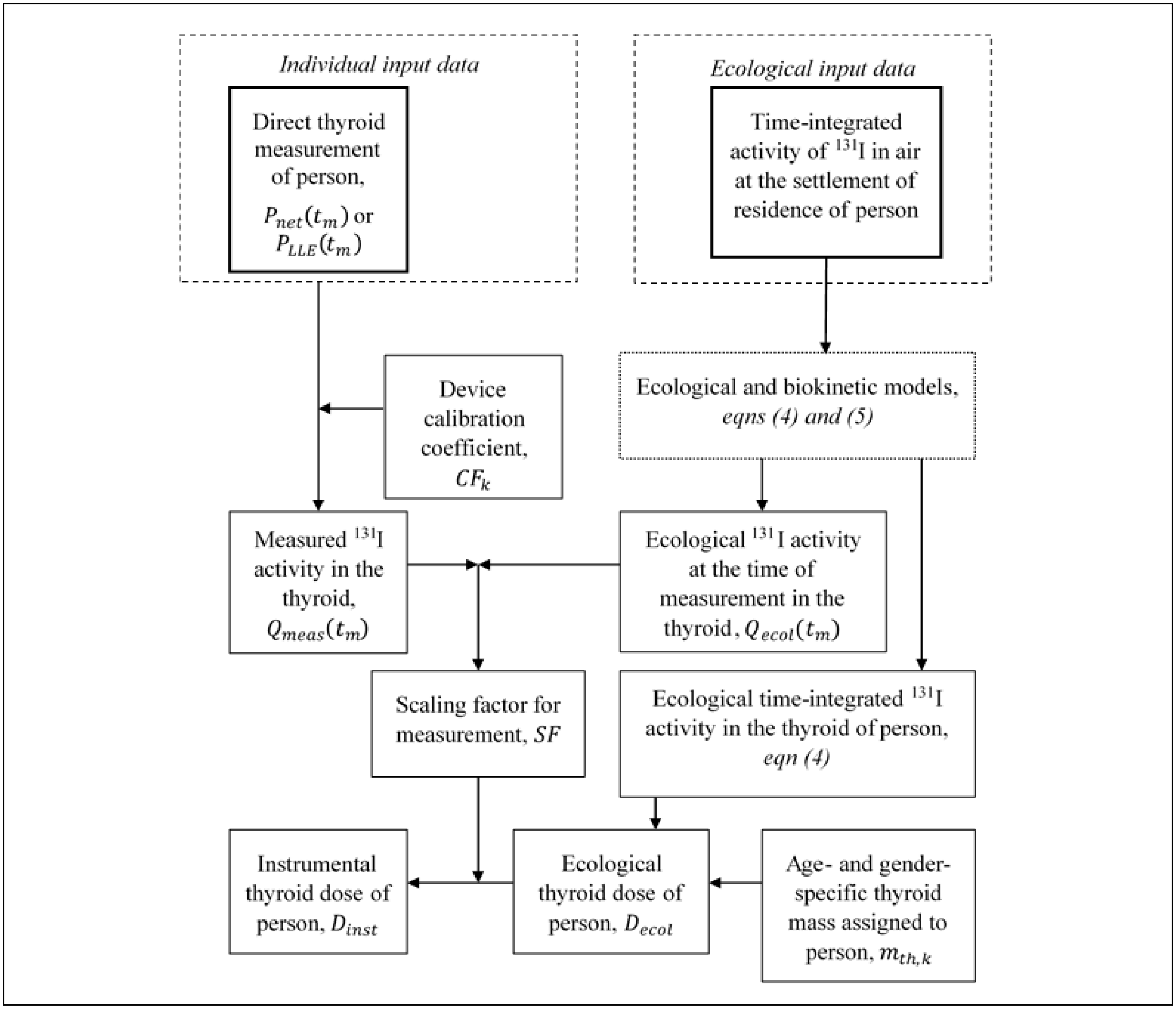
Table A-2.7. Availability of information that should be used to calculate the absorbed doses in the thyroids of those measured

Information	*Availability of information for measurements*			
	[Kim et al., 2020]	*[Kurihara et al., 2016]*	*[Uchiyama et al., 2015]*	*[Tokonami et al., 2012]*
Direct thyroid measurement				
Number of persons	1 080	3	1	62
Results of direct thyroid measurement	+	+	+	+
Results of measurement of background	+	–	–	–
Characteristics of the device used to measure the ^{131}I in the thyroid	+	–	–	–
Environmental radiation data				
Daily concentration of ^{131}I in ground-level air at location/s where exposure occurred	+	+	+	+

50. The general scheme for estimating thyroid doses from direct thyroid measurements is shown in figure A-2.III. Thyroid doses were estimated using input data specific to each individual (direct thyroid measurement) and ecological data (^{131}I concentrations in ground-level air at the location/s where the exposure occurred). Ecological and biokinetic models were used to reconstruct the transport of ^{131}I in air to the human thyroid through intake by inhalation. These models were used to calculate: *(a)* the time-integrated activity of ^{131}I in the thyroid, from which the "ecological dose" was derived; and *(b)* the activity of ^{131}I in the thyroid at the time of the direct thyroid measurement, called the "ecological" ^{131}I activity in the thyroid. To calculate the

"instrumental" or realistic thyroid dose, the ecological dose was scaled by so-called "scaling factor" that is the ratio of ecological ^{131}I activity in the thyroid at the time of measurement to ^{131}I activity in the thyroid derived from the direct thyroid measurement. All steps of dose calculations are discussed in the following sections.

Figure A-2.III. The general scheme of thyroid dose calculation using direct thyroid measurement



51. Unfortunately, important information for each measured person (i.e., that could be obtained by means of a personal interview) was not available, such as: changing clothes and washing before measurements; residential history from the time of the accident until the date of measurement; consumption of locally produced foodstuffs and drinking water, administration of stable iodine to block the uptake of radioiodine to the thyroid.

52. As personal interviews with those measured were not conducted, the following assumptions were made:

- There was no consumption of locally produced foodstuffs that may have contained ^{131}I, i.e., intakes of ^{131}I only by inhalation and drinking of tap water were considered;
- There was no administration of stable iodine among measured individuals to block the uptake of ingested or inhaled radioiodine to the thyroid.

C. Residential history

53. The residential history was not available for the measured individuals, so the following assumptions were made:

- *(a)* Iwaki City, Kawamata Town: permanent residence at the location where a measurement was made, as assumed by Kim et al. [Kim et al., 2020];
- *(b)* Iitate Village: four scenarios of evacuation and residence were assumed according to Ohba et al. [Ohba et al., 2020]:
  - IT1: evacuation to Koriyama City on 16 March 2011 (30% of population);
  - IT2: evacuation to Fukushima City via Kawamata Town on 15 March 2011 and then to Aizu on 21 March 2011 (24% of population);
  - IT3: evacuation to distant areas on 19 March 2011 (25% of population); and
  - IT4: permanent residence at Iitate Village (21% of population);
- *(c)* Tokai Village and Tamura Town: permanent residence at the location where a measurement was made;
- *(d)* Minamisoma City: two groups with low and high levels of ^{131}I in the thyroid were found reflecting two scenarios of residence according to Kawai et al. [Kawai et al., 2018]:
  - Minamisoma 1: evacuation to Date City on 15 March 2011 (persons with low levels of ^{131}I in the thyroid in the range from 0.006 to 0.13 kBq on 16 April 2011); and
  - Minamisoma 2: evacuation to Niigata Prefecture on 23 March 2011 (persons with high levels of ^{131}I in the thyroid in the range from 0.13 to 1.1 kBq on 16 April 2011);
- *(e)* Namie Town: two groups with low and high levels of ^{131}I in the thyroid were found reflecting two scenarios of residence according to Kawai et al. [Kawai et al., 2018]:
  - Namie 1: evacuation to Nihonmatsu City on 15 March 2011 (persons with low levels of ^{131}I in the thyroid in the range from 0.044 to 0.093 kBq on 13–15 April 2011); and
  - Namie 2: permanent residence at the location where a measurement was made was assumed (persons with high levels of ^{131}I in the thyroid in the range from 0.38 to 1.5 kBq on 13–14 April 2011).

D. Measurements of ^{131}I in the thyroids of residents of (or evacuees from) Iitate Village, Iwaki City and Kawamata Town

54. The number of individuals measured in each municipality are summarized in table A-2.8 together with the date when the measurements were made.

Table A-2.8. Distribution of 1,080 individuals measured by date and location

Date in 2011	*Iitate Village*	*Iwaki City*	*Kawamata Town*	*Total*
26 March		46		46
27 March		88		88
28 March			219	219
29 March			272	272
30 March	299		156	455
Total	299	134	647	1 080

55. According to Hosokawa et al. [Hosokawa et al., 2013], the thyroid measurements were performed using NaI(Tl) scintillator (25.4 mm × 25.4 mm survey meters TCS-171 and TCS-172 (Hitachi-Aloka Medical, Ltd.). The operators recorded results of measurements as ambient dose equivalent rates (referred to hereafter as dose rates) in units of µSv/h for each measured individual as follows: the average dose rate from 3 measurements (duration of 30 seconds each) done in geometry "detector against thyroid"; and measurements of background but it was unclear where these were made. Kim et al. [Kim et al., 2020] indicate that background measurements were made on another part of the body of measured individuals without specifying whether it was against the shoulder, stomach or other parts of the body.

1. Background radiation in the room where measurements were performed

56. When the background radiation in the room was measured during the direct thyroid measurements, the net exposure rate was calculated as:

$$P_{net}(t_m) = P_m(t_m) - P_{bg}(t_m) \tag{A-2.1}$$

where $P_m(t_m)$ is the dose rate measured near the thyroid gland (µSv/h); $P_{bg}(t_m)$ is the background radiation (µSv/h) in the room where the measurements were performed; and $P_{net}(t_m)$ is the net dose rate (µSv/h).

2. Lower limits of exposure rate

57. For 598 (55.4% of the total) of the 1,080 individuals measured, the dose rate measured near the thyroid was recorded as equal to or less than the background radiation measurement. In order to prevent the use of these values of net dose rate, $P_{net}(t_m)$, for the direct thyroid measurements, such values, when they occurred, were replaced with lower limits of dose rate. The values of lower limits of dose rate depend on the type of device and on the magnitude of the dose rate due to background radiation in the room. The lower limits of dose rate (µSv/h) were calculated using the following equation [ISO, 2000]:

$$P_{LLDR}(t_m) = \frac{t_p^2}{2 \cdot k \cdot T \cdot \delta^2} \cdot (1 + \sqrt{1 + \frac{8 \cdot k \cdot P_{bg}(t_m) \cdot T \cdot \delta^2}{t_p^2}}) \tag{A-2.2}$$

where t_p^2 = 1.96 is the Student statistics; k is the scale coefficient for the device from impulse to scale reading and is equal to 460 (counts/s per µSv/h) for the TCS-172 device (derived from [Suh and Kurihara, 2013]); T=30 s is the duration of measurement; δ=1 is the relative error of measurement (unitless).

58. The lower limits of dose rate values, which were assigned to 598 measured individuals, vary from 0.006 µSv/h to 0.011 µSv/h.

(a) Contribution to the measured signal from radionuclides on the body and clothes of measured people

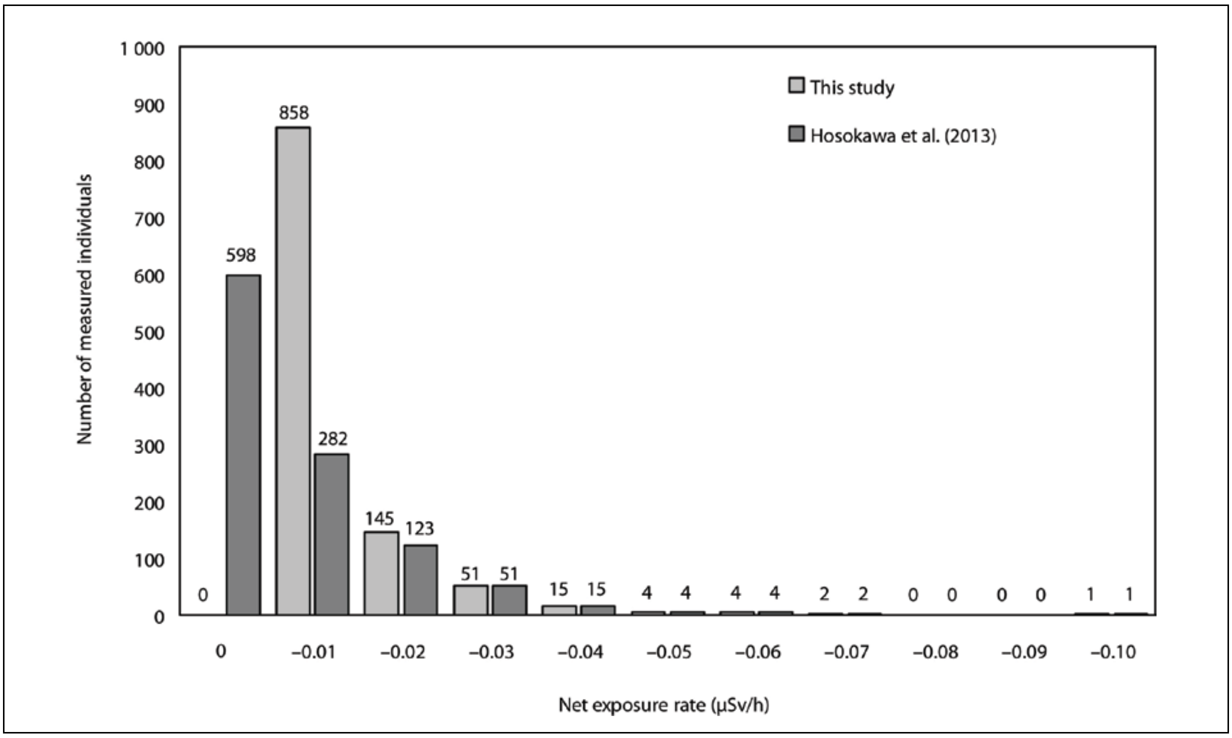
59. Ohba et al. [Ohba et al., 2017] addressed the issue of radionuclides on the body and clothes of those evacuated from a 20-km zone around FDNPS who were measured between 12 and 17 March 2011. However, the Committee did not make any allowance for this in its assessment as, according to Hosokawa et al. [Hosokawa et al., 2013] it was assumed, based on

monitoring before direct thyroid measurements, that there was no surface contamination of the body and clothes of measured individuals.

(b) Dose rate used to calculate ^{131}I in the thyroid

60. The dose rates used by the Committee in estimating the levels of ^{131}I in the thyroid are compared in figure A-2.IV with those of Japanese scientists. The use of the lower limits of dose rate concept eliminates zero values of net exposure rate, $P_{net}(t_m)$. However, around 80% (858 from 1,080) of the measurements resulted in values of net exposure rate equal to or less than 0.01 µSv/h.

Figure A-2.IV. Comparison of dose rates obtained in this study with those obtained by Hosokawa et al. [Hosokawa et al., 2013]



(c) Iodine-131 in the thyroid

61. Assuming that there were no radionuclides on the surface of the body and clothes of measured individuals, the net dose rate, $P_{net}(t_m)$, is only due to the ^{131}I in the thyroid of the subject at the time of the measurement. The relationship between $P_{net}(t_m)$ and the ^{131}I in the thyroid is as follows:

$$Q_{meas}(t_m) = P_{net}(t_m) \cdot CF_k \qquad \text{(A-2.3)}$$

where $Q_{meas}(t_m)$ is the activity of ^{131}I measured in the thyroid (kBq); CF_k is the device calibration coefficient for a person of age k (kBq per µSv/h).

(d) Calibration coefficients for scintillator survey meter TCS-172

62. The direct measurements of ^{131}I in the thyroids of people affected by the accident at FDNPS were made using devices not specifically designed for this purpose. Therefore, Japanese scientists needed to estimate age-dependent calibration factors for ^{131}I for the survey meter TCS-172.

63. Calibration coefficients were obtained using Monte Carlo simulations of the NaI(Tl) survey meter and age-specific phantoms modified by Ulanovsky and Eckerman [Ulanovsky and Eckerman, 1998] and have been published by Kim et al. [Kim et al., 2020]. Table A-2.9 gives values of age-dependent calibration coefficients, CF_k, obtained by Kim et al. [Kim et al., 2020] for different distances between detector and the neck of the measured person as well as values used by Kim et al. [Kim et al., 2020] for estimates of the activity of ^{131}I in the thyroid. To be consistent with the analysis of Kim et al. [Kim et al., 2020], the same values of CF_k have been used by the Committee.

Table A-2.9. Age-dependent calibration coefficients, CF_k, (kBq per μSv/h) obtained by Kim et al. [Kim et al., 2020]

Age	*CF_k (kBq per μSv/h) Distance between detector and the neck (mm)*			*CF_k (kBq per μSv/h) Used by Kim et al. [Kim et al., 2020] and by the Committee*
	0	*5*	*10*	
Newborn	11.0	15.2	20.0	16.8
1 year	12.4	16.7	21.7	18.5
5 years	13.8	18.4	23.6	20.1
10 years	17.9	22.9	28.7	25.4
15 years	21.1	26.6	32.7	29.4
20 years (adults)	24.2	29.8	36.0	33.0

E. Dosimetry model

64. The ecological and biokinetic models were used to reconstruct the transport of ^{131}I from the environment to the thyroids of people from intakes by inhalation and ingestion. The models used for this purpose have been described in sections IV, V and VI for intakes by the respective pathways, i.e., estimation of the time-integrated concentration of ^{131}I in the thyroid, from which the so-called “ecological dose” is derived, and the activity of ^{131}I in the thyroid at the time of its measurement, called the “ecological” activity of ^{131}I in the thyroid. To calculate the so-called “instrumental” or realistic thyroid dose, the “ecological dose” has been scaled by so-called “scaling factor” that is the ratio of the activity of ^{131}I in the thyroid derived from the direct thyroid measurement to the ecological ^{131}I activity in the thyroid at the time of measurement.

1. Ecological dose

65. The following equation was used to calculate “ecological” thyroid doses due to ^{131}I intake (see figure A-2.III):

$$D_{ecol} = \frac{13.82 \cdot E_{th,k}}{m_{th,k}} \cdot \int_{0}^{\infty} Q_{ecol}(t)dt \qquad \text{(A-2.4)}$$

where D_{ecol} is the thyroid dose due to ^{131}I intake (mGy); 13.82 is a unit conversion factor ((Bq/kg)(g/kg)(J/MeV)(s/d)(mGy/Gy)); $E_{th,k}$ is the mean energy absorbed in the thyroid per decay of ^{131}I in the thyroid [Mowlavi et al., 2011] (MeV); $m_{th,k}$ is the sex-specific thyroid mass for person of age k [ICRP, 2002](g); and $Q_{ecol}(t)$ is the variation with time of ecological activity of ^{131}I in the thyroid (Bq) that is described by equations A-2.5 to A-2.7.

2. Ecological activity of ^{131}I in the thyroid

66. Two pathways of ^{131}I intake were considered in this study: inhalation of air and ingestion of tap water containing radioiodine.

67. The activity of ^{131}I in the thyroid at day *t* from inhalation was calculated as:

$$Q_{ecol,inh}(t) = Q_{ecol,inh}(t-1) \cdot e^{-(\lambda_{th,k}+\lambda_{r,I-131})\cdot \Delta t} + C_{air}^{I-131}(t) \cdot B_k \cdot F_{in} \cdot w_{inh} \cdot w_{th} \qquad \text{(A-2.5)}$$

where $Q_{ecol,inh}(t)$ is the ecological activity of ^{131}I in the thyroid due to inhalation (kBq) at day *t* with initial condition of $Q_{ecol,inh}(0) = 0$; $Q_{ecol,inh}(t-1)$ is the ecological activity of ^{131}I in the thyroid at day *t*-1 (kBq); Δt = 1 d is the calculation step; $C_{air}^{I-131}(t)$ is the time-integrated concentration of ^{131}I in air at the location of residence during the day *t* ((kBq d)/m^3); B_k is the daily-average breathing rate for a person of age k [ICRP, 2002] (m^3/d); F_{in} is the ratio of the activity of ^{131}I inhaled in air during the day while staying indoors and outdoors to the activity of ^{131}I inhaled while staying outdoors for the entire day (determined by the time spent indoors and the reduction in the concentration of ^{131}I air while there in comparison with being outdoors (see table A-2.10)) – the reduction in the concentration of ^{131}I in air indoors was assumed to be 0.5; w_{inh} = 0.66 is the fraction of inhaled iodine transferred to blood [ICRP, 1995] (unitless); w_{th} = 0.15 is the Japan-specific fraction of iodine uptake by the thyroid (unitless).

68. The activity of ^{131}I in the thyroid at day *t* due to ingestion of tap water was calculated as:

$$Q_{ecol,ing}(t) = Q_{ecol,ing}(t-1) \cdot e^{-(\lambda_{th,k}+\lambda_{r,I-131})\cdot \Delta t} + DW^{I-131}(t) \cdot V_{DW,k} \cdot w_{ing} \cdot w_{th} \qquad \text{(A-2.6)}$$

where $Q_{ecol,ing}(t)$ is the ecological activity of ^{131}I in the thyroid due to ingestion (kBq) at day *t* with initial condition of $Q_{ecol,ing}(0) = 0$; $Q_{ecol,ing}(t-1)$ is the ecological activity of ^{131}I in the thyroid at day *t*-1 (kBq); Δt = 1 d is the calculation step; $\lambda_{th,k} = \ln(2)/T_{b,k}$ is the rate of biological elimination of iodine from the thyroid for a person of age k (d^{-1}); $T_{b,k}$ is the biological half-time of iodine removal from the thyroid for a person of age k [ICRP, 1993] (d); $\lambda_{r,I-131}$ = 0.0862/d is the radioactive decay rate of ^{131}I; $DW^{I-131}(t)$ is the concentration of ^{131}I in tap water at the location of residence at day *t* (kBq/L); $V_{DW,k}$ is the daily consumption of tap water for person of age k (L/d); $w_{ing} = 1.0$ is the fraction of ingested iodine transferred to blood [ICRP, 1993] (unitless).

69. The total ecological activity of ^{131}I in the thyroid was calculated as the sum of ecological amounts from inhalation and ingestion:

$$Q_{ecol}(t) = Q_{ecol,inh}(t) + Q_{ecol,ing}(t) \qquad \text{(A-2.7)}$$

Table A-2.10. Age- and sex-dependent parameters of the dosimetry model

Age (years)	$m_{th,k}$ *(g)*		*Hours per day indoors*		*Breathing rate (m^3/d)*		*Drinking water consumption (L/d)*	
	M	*F*	*M*	*F*	*M*	*F*	*M*	*F*
0	1.3	1.3	24	24	2.86	2.86	0.42	0.42
1	1.8	1.8	21.6	21.6	5.16	5.16	1.00	0.83
2	2.2	2.2	21.6	21.6	6.05	6.05	1.04	0.86
3	2.6	2.6	21.6	21.6	6.94	6.94	1.07	0.89
4	3.0	3.0	21.6	21.6	7.83	7.83	1.11	0.92
5	3.4	3.4	21.6	21.6	8.72	8.72	1.15	0.95
6	4.3	4.3	21.6	21.6	10.0	10.0	1.18	0.98
7	5.2	5.2	21.6	21.6	11.4	11.4	1.22	1.01
8	6.1	6.1	21.6	21.6	12.7	12.7	1.26	1.04
9	7.0	7.0	21.6	21.6	14.0	14.0	1.30	1.07
10	7.9	7.9	21.6	21.6	15.3	15.3	1.33	1.11
11	8.7	8.7	21.6	21.6	16.3	15.4	1.37	1.14
12	9.5	9.5	21.6	21.6	17.2	15.5	1.41	1.17
13	10.4	10.4	21.6	21.6	18.2	15.6	1.44	1.20
14	11.2	11.2	21.6	21.6	19.1	15.7	1.48	1.23
15	12.0	12.0	21.6	21.6	20.1	15.8	1.52	1.26
16	13.6	13.0	21.4	21.4	14.4	11.4	1.55	1.29
17	15.2	14.0	21.1	21.1	14.7	11.7	1.59	1.32
18	16.8	15.0	20.9	20.9	15.0	12.1	1.63	1.35
19	18.4	16.0	20.6	20.6	15.2	12.4	1.66	1.38
20	20.0	17.0	20.4	20.4	22.2	17.8	1.70	1.41

3. Instrumental dose

70. The instrumental thyroid dose of subject k was calculated using the following equation:

$$\begin{aligned} D_{inst} &= \frac{Q_{meas}(t_m)}{Q_{ecol}(t_m)} \cdot (D_{ecol,inh} + D_{ecol,ing}) = SF \cdot (D_{ecol,inh} + D_{ecol,ing}) \\ &= D_{inst,inh} + D_{inst,ing} \end{aligned} \quad \text{(A-2.8)}$$

where $Q_{meas}(t_m)$ is the activity of ^{131}I measured in the thyroid calculated using equation A-2.3 (kBq); $Q_{ecol}(t_m)$ is the ecological activity of ^{131}I in the thyroid at the time of measurement t_m calculated using equation A-2.7 (kBq); and SF is a scaling factor (unitless).

4. Model parameters

(a) Biokinetic parameters

71. The Committee estimated the amounts of ^{131}I in measured thyroids and the related absorbed doses for intakes by inhalation and ingestion using biokinetic models of ICRP [ICRP,

1989; ICRP, 1993; ICRP, 1995], albeit corrected for Japan-specific iodine uptake by thyroid (see section IV).

(b) Thyroid mass

72. The thyroid mass is one of the most important parameters in the estimation of thyroid doses and uncertainty in its value is the major contributor to the overall uncertainty when estimating thyroid doses [Drozdovitch et al., 2015]. The Committee used age- and sex-specific values of the thyroid mass from ICRP Publication 89 [ICRP, 2002] to calculate thyroid doses (see table A-2.10).

(c) Number of hours spent indoors

73. The number of hours spent indoors by different age groups in the population were those specified in attachment A-4 in the estimation on external doses from deposited radionuclides (see table A-2.10).

(d) Breathing rate

74. Breathing rates were taken from ICRP [ICRP, 2002] and are summarized in table A-2.10 for various ages.

(e) Drinking water consumption

75. Daily consumption of tap water was taken to be 1.0 L for 1-year-old infant and 1.7 L for adults [Hirakawa et al., 2017] and 1.5 L for 10-year-old children. Consumption by females was adjusted by a factor of 0.83 derived from an analysis of water consumption in Japan [IAEA, 1998]. Daily consumption for 3-month-old infants was taken to be 0.42 L based on assumed breastfeeding, a transfer coefficient of ^{131}I of 0.37 (d/L) from intake to breast milk [Simon et al., 2002], and consumption of breast milk by an infant of 0.8 L/d. It should be noted, that there is variability in daily consumption of drinking water reported in literature from 0.71 L to 1.3 L for a 1-year-old infant, from 1.55 L to 2.2 L for a 10-year-old child and from 1.55 L to 2.3 L for adults [Miyatake et al., 2020; Murakami and Oki, 2014].

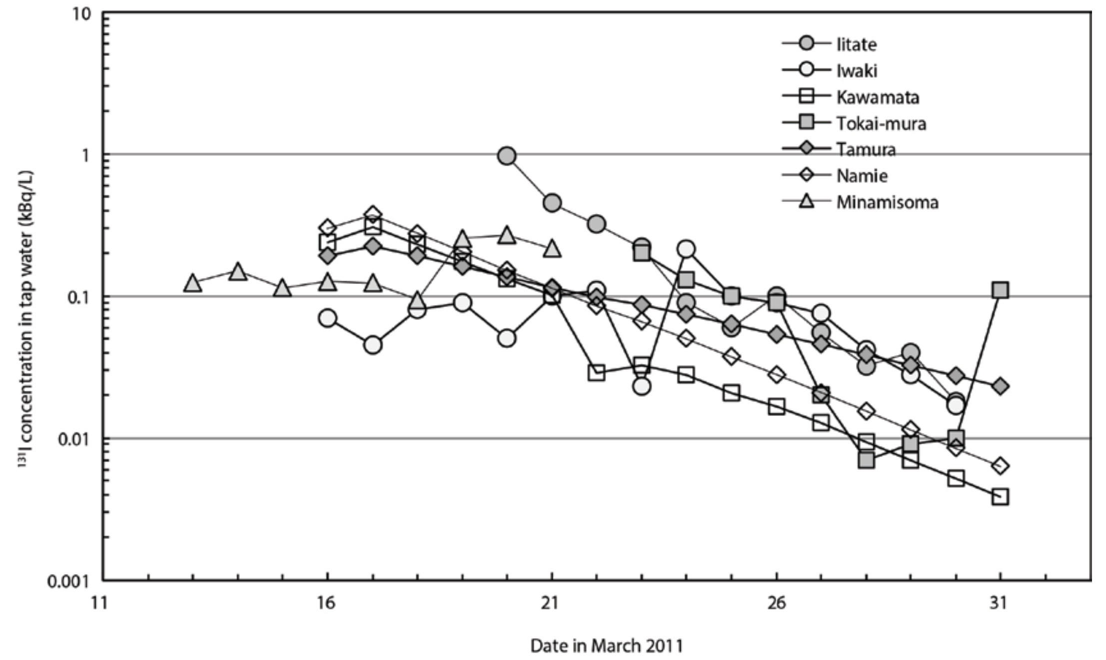
(f) Iodine-131 concentrations in air at locations and times where those measured were exposed

76. Daily time-integrated concentrations of ^{131}I in air were obtained using the modelling approach described in section V. Population-weighted arithmetic mean values of the daily time-integrated concentrations were estimated for permanent residents of one or other municipality where thyroid measurements were made. For evacuees, account was taken of their whereabouts before, during and after evacuation in estimating the population-weighted daily integrated air concentrations. For some municipalities different evacuation routes were followed by different groups resulting in them being exposed to different concentrations of ^{131}I (see section VII.C and table A9 in appendix A). In such cases (e.g., Iitate Village) the daily population-weighted mean concentrations were estimated taking account of the fraction of the evacuated population evacuating by the different routes.

(g) Iodine-131 concentrations in tap water

77. Iodine-131 concentrations in tap water for each of the municipalities where thyroids were measured were estimated by [Miyatake et al., 2020] and derived from [Kim et al., 2020; Kinase et al., 2014; Murakami and Oki, 2014]. Figure A-2.V shows the variation with time of measured ^{131}I activity concentration in tap water in locations with direct thyroid measurements (restrictions are not shown).

Figure A-2.V. Variation with time of measured ^{131}I concentration in tap water in locations with direct thyroid measurements (restriction in water consumption are not shown)



VIII. VALIDATION OF THE MODELS AND APPROACHES USED BY THE COMMITTEE FOR ESTIMATING DOSES FROM THE INTAKE OF ^{131}I BY INHALATION AND INGESTION

78. Thyroid doses, estimated by the Committee using models and approaches that it judged appropriate for these purposes, have been compared with those derived from direct measurements of thyroids. The modelled doses were estimated following the approaches set out in sections IV, V and VI of this attachment – but only for the intake of ^{131}I as shorter-lived isotopes of iodine would no longer have been present in the thyroids of those measured at the time/s of measurement. The modelled ingestion doses were based on analyses undertaken by [Miyatake et al., 2020; Murakami and Oki, 2014] and are summarized in table A-2.11.

Table A-2.11. Indicative estimates of thyroid doses from ingestion based on references [Miyatake et al., 2020; Murakami and Oki, 2014]

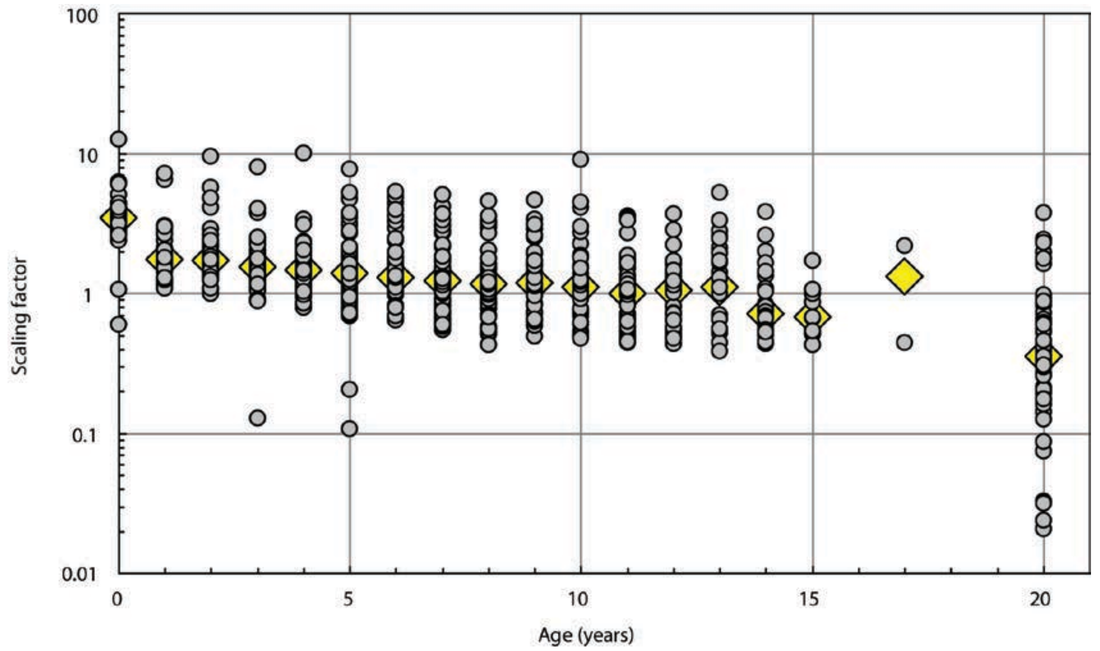
Location	*Absorbed dose to thyroid due to ^{131}I ingestion (mGy)*		
	Adults	*10-year old*	*1-year old*
Permanent residents of Fukushima Prefecture, both food and drinking water	0.42	0.94	1.1
Evacuees from Iitate Village (mean/median), drinking water	1.1/1.0	2.3/2.1	3.6/3.3

79. Comparison of the modelled doses estimated by the Committee and those derived from individual thyroid measurements was made in terms of the ratio “modelled dose” to “instrumental dose”, unitless, in two ways: *(a)* comparison of the median modelled dose (from inhalation and ingestion) with median instrumental dose derived from direct thyroid measurements, for each age and municipality where measurements were made; and *(b)* comparison of the median modelled dose (from inhalation and ingestion) with individual instrumental dose derived from direct thyroid measurements on 1,103 persons. This comparison does not include 40 persons from Minamisoma City (scenario 1) and Namie Town (scenario 1) who were evacuated shortly after the accident.

A. Issues with scaling factors

80. The values of the scaling factors for 1,146 individuals with direct thyroid measurements are shown in figure A-2.VI as a function of the age of those measured. The value of SF varies with decreasing age and is most apparent for ages less than about 7 years. Such age dependence was not observed among 11,732 subjects of the Belarusian-American cohort [Drozdovitch et al., 2013] and 13,204 subjects of the Ukrainian-American cohort [Masiuk, 2019].

Figure A-2.VI. Scaling factor for 1,146 measured individuals versus age. Yellow diamonds show median of scaling factors for given age



81. The possible reasons for this trend or bias include: *(a)* particularities in the behaviour and lifestyle for children that were not considered in the modelled dose estimates; *(b)* different geometry of the measurements (e.g., distance between the neck and the probe or/and part of the body where measurements of background were made) applied for younger and older children during the measurements; *(c)* calibration factors for the thyroid detectors used to measured individuals; *(d)* higher iodine uptake by the thyroids of younger children owing to dietary habits more akin to those in the west. To eliminate bias related to the age of measured individuals, values of the scaling factor were analysed for each location of measurement and values of the scaling factor for young children were adjusted to those for age of 10 years and older. Scaling factors for Minamisoma City and Namie Town were not adjusted, as bias related to age was not observed for these locations.

B. Thyroid doses derived from thyroid measurements

82. The general characteristics of the doses derived from measurements of the thyroids of 1,080 individuals are shown in table A-2.12 for three municipalities. Those measured in Iitate Village received the highest doses (arithmetic mean of 6.0 mGy), followed by Iwaki City (4.1 mGy) and Kawamata Town (4.0 mGy). The maximum dose was 50 mGy for an individual measured in Iitate Village.

Table A-2.12. General characteristics of thyroid doses (mGy) derived from thyroid measurements

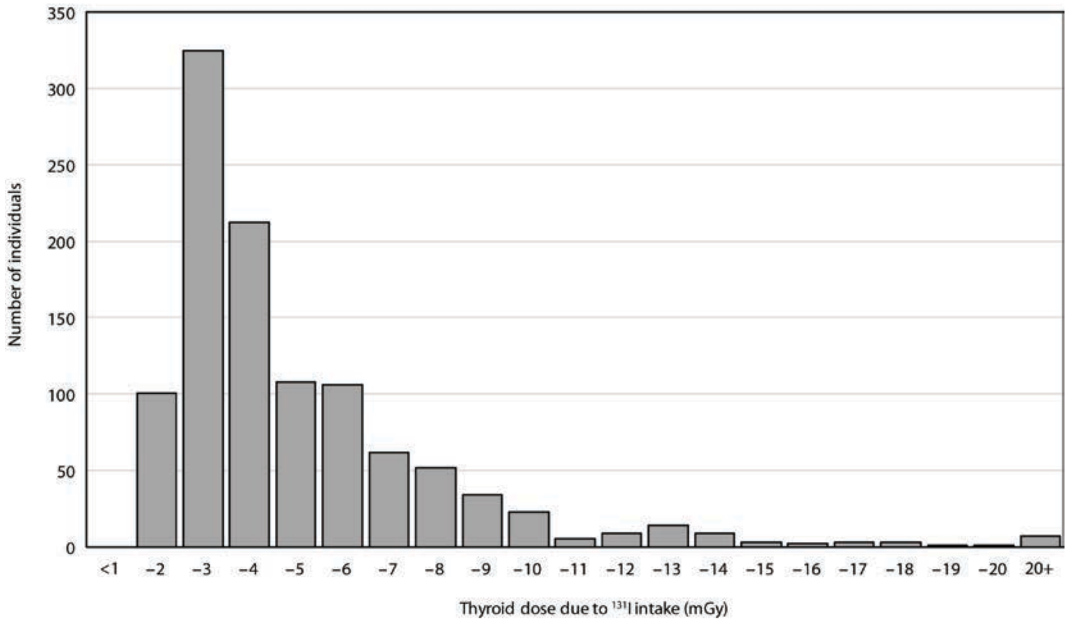
Parameter	*Iitate Village*	*Iwaki City*	*Kawamata Town*	*Total*
Number of individuals	299	134	647	1 080
Arithmetic mean	6.0	4.1	4.0	4.6
Median	4.9	3.0	3.3	3.5
Range	1.8–50	1.0–26	1.2–23	1.0–50

83. The distribution of thyroid doses derived from measurements of the thyroid are shown in table A-2.13 for each municipality where measurements were made; the overall distribution is shown in figure A-2.VII. For 645 individuals of 1,080 measured (59.7%), the thyroid doses were estimated to be in the range 2.0–4.99 mGy. Fifty-seven individuals (5.3% of the total) were estimated to have received thyroid doses of 10 mGy or more.

Table A-2.13. Distribution of 1,080 individuals with direct thyroid measurements by location of measurements and range of dose

Interval of thyroid dose (mGy)	*Iitate Village*		*Iwaki City*		*Kawamata Town*		*Total*	
	N	*%*	*N*	*%*	*N*	*%*	*N*	*%*
<1.0								
1.0–1.99	10	3.4	44	32.8	47	7.3	101	9.4
2.0–4.99	143	47.8	55	41.1.	447	69.1	645	59.7
5.0–9.99	110	36.8	28	20.9	139	21.4	277	25.6
≥10.0	36	12.0	7	5.2	14	2.2	57	5.3
Entire study	299	100.0	134	100.0	647	100.0	1 080	100.0

Figure A-2.VII. Distribution of thyroid doses, derived from direct thyroid measurements, of 1,080 individuals in a few municipalities of Fukushima Prefecture



C. Comparison of thyroid doses derived from measurements with estimates published by others

84. The Committee has compared its estimates of thyroid doses derived from measurements of thyroids with those of Kim et al. [Kim et al., 2020]. Kim et al. considered two scenarios of ^{131}I intake:

- Scenario 1: single intake via inhalation on 15 March 2011; and
- Scenario 2: repeated intake via ingestion at a uniform rate from 16 March 2011 to the day before measurements.

85. The two estimates are compared in table A-2.14 for Iitate Village, Iwaki City and Kawamata Town. Comparisons, however, can only be made for some of the quantities of the respective distributions of dose owing to the different treatment of measurements where the measured dose rate was equal to or less than the background. The Committee, in its assessment, replaced such measured dose rates (for 598 (55%) of the 1,080 measured individuals) by the lower limit, while Kim et al. [Kim et al., 2020] assumed that the activity of ^{131}I in the thyroid was zero, as was the corresponding dose. Meaningful comparisons can, however, be made of the median, upper quartile and maximum doses estimated; those estimated by the Committee can be seen in table A-2.14 to be in reasonable agreement with those of Kim et al. [Kim et al., 2020]. Thyroid doses estimated by the Committee are, in general, close to those estimated by Kim et al. [Kim et al., 2020] for Scenario 1 of inhalation ^{131}I intake. IAEA also analysed the same group of 1,080 measured individuals and concluded that predominant intake of ^{131}I to the children was due to inhalation rather than ingestion [IAEA, 2015].

86. Kim et al. [Kim et al., 2020] also indicated that 73 individuals from among those measured were from municipalities other than where the measurements were made, specifically, from Minamisoma City and Fukushima City and two persons from Ibaraki Prefecture. These individuals were not identified in the information made available to the Committee and are a confounding factor.

87. A comparison is also made in table A-2.15 between the doses estimated by the Committee and those of Kim et al. [Kim et al., 2020] for measurements of the thyroids of residents of Minamisoma City as reported by Tokonami et al. [Tokonami et al., 2012]. Although measurements were made in different groups of people of different ages, broad agreement is observed between the two estimates for the median, upper quartile and maximum of the thyroid dose distributions.

Table A-2.14. Comparison of thyroid doses (mGy) estimated by the Committee from direct measurements of the thyroid and those of Kim et al. [Kim et al., 2020] for Iitate Village, Iwaki City and Kawamata Town

Parameter	*Iitate Village*			*Iwaki City*			*Kawamata Town*		
	This study	*[Kim et al., 2020]*		*This study*	*[Kim et al., 2020]*		*This study*	*[Kim et al., 2020]*	
		Scenario 1	*Scenario 2*		*Scenario 1*	*Scenario 2*		*Scenario 1*	*Scenario 2*
Number of persons	299	291		134	123		647	593	
Minimum (mGy)	1.8	0.0	0.0	1.0	0.0	0.0	1.2	0.0	0.0
Lower quartile (mGy)	2.9	0.0	0.0	1.6	0.0	0.0	2.5	0.0	0.0
Median (mGy)	4.9	3.7	1.6	3.0	2.8	1.5	3.3	0.0	0.0
Upper quartile (mGy)	7.7	7.5	3.3	5.0	8.8	4.5	3.7	3.7	1.6
Maximum (mGy)	50	61	20	26	48	25	23	31	13
Interquartile range (mGy)	4.8	7.5	3.3	3.4	8.8	4.5	1.2	3.7	1.6

Table A-2.15. Comparison of the thyroid doses (mGy) estimated by the Committee from direct measurements of the thyroid and those of Kim et al. [Kim et al., 2020] for Minamisoma City

Parameter	*Minamisoma City*		
	This study	*[Kim et al., 2020]*	
		Scenario 1	*Scenario 2*
Number of persons	45	31	
Minimum (mGy)	0.11	0.0	0.0
Lower quartile (mGy)	1.0	0.0	0.0
Median (mGy)	1.9	2.8	1.3
Upper quartile (mGy)	4.7	7.5	3.3
Maximum (mGy)	27	26	11
Interquartile range (mGy)	3.7	7.5	3.3

1. Variability of individual thyroid doses among those measured

88. The variability of thyroid doses among those measured is shown in figure A-2.VIII where normal probability plots (logarithm of values) are presented for different age groups. Distributions of individual thyroid dose for age groups of 1-year-old infants and 10-year-old children were found to be log-normal and the geometric standard deviation (GSD) characterizes the uncertainty of the doses. Parameters of the distributions of individual thyroid doses for different age groups are given in table A-2.16. Judgements on the form of the distribution of adult doses are less definitive probably because of the relatively small number of adults measured.

Figure A-2.VIII. Normal probability plots of thyroid doses (logarithm of values) of individuals of different ages whose thyroids were measured in one or other municipality of Fukushima Prefecture

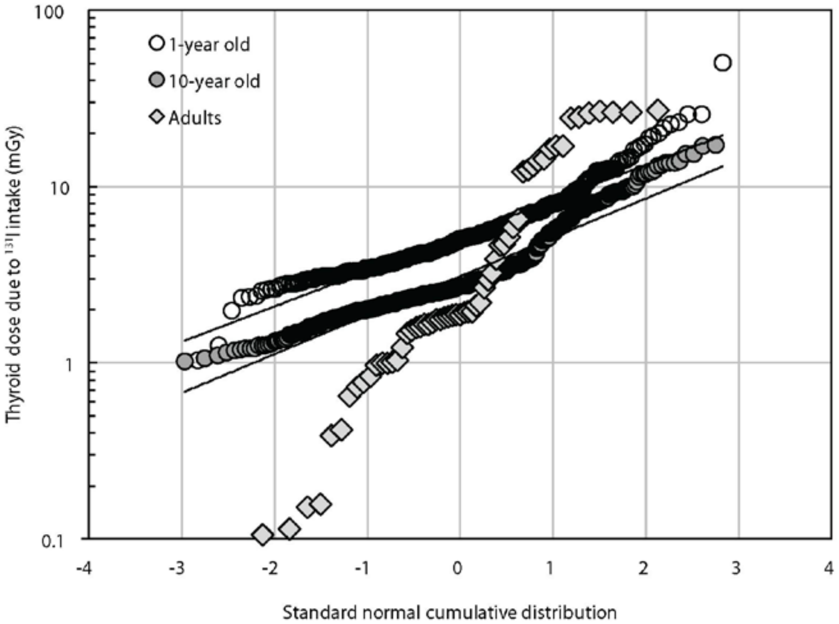


Table A-2.16. Parameters of the distributions of individual thyroid doses derived from thyroid measurements

Population group	*Number of persons*	*Parameters of thyroid doses distribution (relative units)*				*GSD*
		5%	*50%*	*Mean*	*95%*	
1 year (preschool children)	425	0.50	0.84	1.00	2.10	1.8
10 years (school children)	662	0.43	0.75	1.00	2.51	2.1
Adults (>16 years)	56	0.03	0.34	1.00	4.51	4.3
All	1 143	0.35	0.75	1.00	2.58	2.1

2. Uncertainties in thyroid doses derived from measurements

89. The uncertainty of individual thyroid doses is characterized by the GSD for a log-normal distribution of individual stochastic doses calculated for each person using Monte Carlo simulations. The Committee has not made a quantitative assessment of the uncertainties in the doses it has derived from thyroid measurements; rather, it has relied on extensive assessments of uncertainties in thyroid doses derived from thyroid measurements of those exposed to Chernobyl fallout where GSD values ranged from about 1.5 to 1.8 [Drozdovitch et al., 2015; Likhtarov et al., 2014]. Based on the Chernobyl experience, the Committee has made a subjective judgement that a GSD of about 2 would be appropriate for the distribution of individual thyroid dose in the municipalities of Fukushima Prefecture where thyroids were measured.

D. Comparison of modelled and measured thyroid doses from intakes of ^{131}I

90. A comparison of the modelled doses estimated by the Committee and those derived from measurements is given in table A-2.17. Median doses, together with uncertainties in their values (5% and 95% confidence intervals), are presented for each of the municipalities where thyroids were measured. The confidence intervals on the modelled doses were estimated following the approach set out in attachment A-12; those on the measured doses were based on expert judgement (see section VII.B). The modelled doses are, on average, in broad agreement with those derived from direct thyroid measurements. The weighted average ratios over all ages of the modelled and measured median doses range from 0.46–0.91 for the municipalities where measurements were made.

91. The distribution of the ratio of modelled and measured median thyroid doses is shown in figure A-2.IX. The ratio varies over quite a wide range up to values of about 3.7. The mean and median values of the ratio are 0.64 and 0.6, respectively.

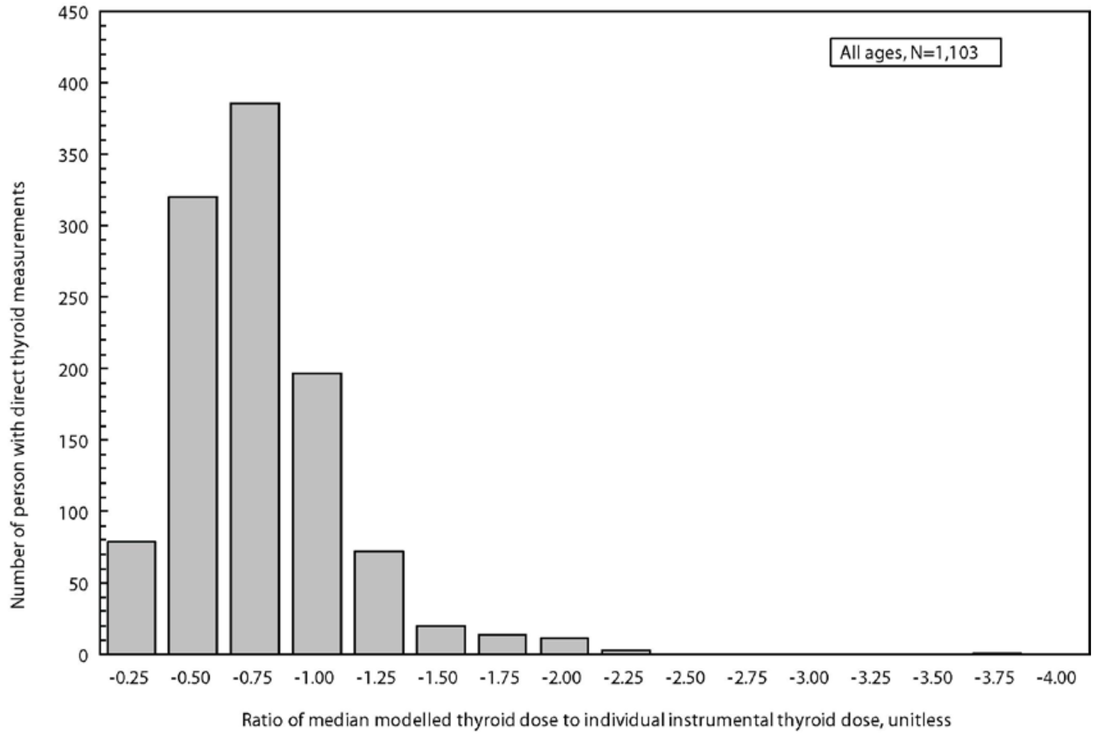
92. The broad agreement between the modelled and measured doses, albeit in a small number of municipalities where thyroid measurements were made, supports the use of the models and approaches adopted by the Committee for estimating thyroid doses to the Japanese population.

Table A-2.17. Comparison[a] of modelled and measured median doses (and 5th and 95th percentiles) to the thyroids of 1,103 individuals whose thyroids were measured in particular municipalities of Fukushima Prefecture

Locality	*Adults (16 years+)*			*10-year old (6–15 years)*			*1-year old (≤5 years)*		
	Model (mGy)	*Thyroid measurements (mGy)*	*Ratio (modelled-to-measured), relative units*	*Model (mGy)*	*Thyroid measurements (mGy)*	*Ratio (modelled-to-measured), relative units*	*Model (mGy)*	*Thyroid measurements (mGy)*	*Ratio (modelled-to-measured), relative units*
Iitate Village	1.42 [0.53–9.8][b]			2.34 [1.1–14]	3.57 (220)[c] [1.1–11]	0.66	2.75 [1.3–16]	7.11 (79) [2.3–22]	0.39
Iwaki City	1.19 [0.53–7.1]			2.21 [1.1–12]	1.75 (79) [0.56–5.5]	1.26	2.64 [1.3–15]	4.55 (55) [1.5–14]	0.58
Kawamata Village	0.95 [0.49–9.1]			1.81 [1.0–15]	2.56 (361) [0.82–8.0]	0.71	2.12 [1.2–18]	4.50 (286) [1.4–14]	0.47
Minamisoma City [d]	5.81 [1.1–41]	6.53 (15) [2.1–20]	0.89	9.9 [2.1–69]			12 [2.5–84]	10.2 (1) [3.3–32]	1.17
Namie Town	21.5 [2.6–281]	20.7 (6) [6.6–65]	1.04	36.0 [4.6–467]			41.3		
Tamura City	0.50 [0.43–3.0]	1.22 (1) [0.39–3.8)]	0.41	1.07 [0.96–5.3]			1.24		
Mean ratio [e]			0.91			0.76			0.47

[a] Limited to 1,103 of the 1,146 thyroid measurements, as meaningful comparisons could not be made for the others.
[b] Fifth and 95th percentiles given in square brackets.
[c] Number of measured individuals given in parenthesis.
[d] Excluding those evacuated soon after the accident.
[e] Weighted by number of measured individuals.

Figure A-2.IX. Distribution of the ratios of modelled to measured thyroid doses, unitless



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