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ORIGINAL ARTICLE

Reliability of thyroid doses due to ^{131}I intake exceeding 5 Gy in a cohort of Belarusian children exposed to Chernobyl fallout

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Abstract
High thyroid doses due to Iodine-131 (^{131}I) intake among individuals exposed in childhood and adolescence to Chernobyl fallout raise questions about their reliability and their impact on the analysis of the radiation-related risk of thyroid cancer and other thyroid diseases in the exposed population. In the present study, an in-depth examination was conducted of thyroid doses from ^{131}I intake over 5 Gy calculated for 131 subjects of the Belarusian-American cohort of individuals exposed after the Chernobyl accident. Thyroid doses in this cohort study were estimated based on individual radiation measurements of ^{131}I thyroidal activity and detailed questionnaire data on individual behavior and consumptions of locally produced foodstuffs. Therefore, these doses provide the best basis for assessing reliability. The analysis showed that the result of direct thyroid measurement was mistakenly assigned to three out of 131 study subjects (2.3% of the total), and, therefore, the instrumental thyroid dose for these individuals cannot be correctly estimated. This study confirmed with a high degree of confidence the reliability of thyroid doses due to ^{131}I intake exceeding 5 Gy that were calculated for the Belarusian-American cohort members.

Keywords Chernobyl · Thyroid · ^{131}I · Radiation dose · 5 gy · Reliability

Introduction

Almost 35 years have passed since the Chernobyl accident occurred on 26 April 1986, which is still the most severe in the history of the nuclear reactor industry. Following the accident, a large amount of radioactive material was released into the atmosphere, including 1.8×10^{18} Bq of the most radiologically significant radionuclide, Iodine-131 (^{131}I) (UNSCEAR 2011). Many radiation epidemiological studies have been conducted to assess the possible radiation-related health consequences of the accident, especially after exposure of the thyroid gland in childhood to ^{131}I (e.g., Astakhova et al. 1998; Cahoon et al. 2017; Cardis et al. 2005; Tronko et al 2017; Zablotska et al. 2011). The credibility of the radiation-related risk of health effects is largely determined by the quality of dose estimates used in these studies. Because study subjects with high doses can have a strong impact on radiation dose–response estimates, a careful examination of the reliability of dose estimates over 5 Gy is important.

In the present study, an in-depth examination of thyroid doses from ^{131}I intake over 5 Gy calculated for the Belarusian-American cohort of children exposed to Chernobyl fallout was conducted. The dose estimates were based on the following data available for all 11,732 cohort members: (1) measurements of the exposure rate against the subjects' necks, which were performed within two months after the accident and allowed to estimate the ^{131}I thyroidal activity for the measured person; and (2) responses to personal interviews of the study subjects or their relatives on residential history after the accident and dietary habits (Drozdovitch et al. 2013). This paper considers 131 out of 11,732 Belarusian-American cohort members with thyroid doses due to ^{131}I intake above 5 Gy, including 34 with doses higher than 10 Gy. To check the reliability of high doses, this paper examined the input data used for dose reconstruction as well

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as the questionnaire data that are available from repeated personal interviews of the study subjects or their relatives.

Materials and methods

Study population

Table 1 shows the distribution of 131 study subjects with thyroid doses due to ^{131}I intake of more than 5 Gy by age at the time of the accident (ATA). Among the individuals included in the study, 106 (80.9% of the total) were younger than 5 y ATA and 25 (19.1% of the total) were between 5 and 15 y old. The mean age of subjects ATA was 3.6 ± 3.5 years. One hundred twenty-eight subjects resided ATA in Gomel Oblast, two subjects resided ATA in Minsk City, and one in Mogilev Oblast. Sixty-seven out of 131 (51.1% of the total) study subjects lived ATA in settlements in the 30-km zone around the Chernobyl nuclear power plant where the highest deposition of ^{131}I occurred and which were evacuated shortly after the accident.

Table 1 Distribution of the study subjects according to age at the time of the accident (ATA) and thyroid doses due to ^{131}I intake according to Drozdovitch et al. (2013)

Age ATA (y)	Mean thyroid doses (Gy)	Number of persons with thyroid doses (Gy) in range		Total	% of the total
		5.0–9.99	10.0+		
< 1.0	9.3	9	6	15	11.5
1.0–1.99	9.5	23	15	38	29.0
2.0–2.99	9.0	21	5	26	19.7
3.0–3.99	8.4	19	4	23	17.6
4.0–4.99	6.0	4	–	4	3.1
5.0–9.99	6.8	15	1	16	12.2
10.0+	9.2	6	3	9	6.9
Entire study	8.7	97	34	131	100.0

Calculation of thyroid doses

Figure 1 shows a simplified schema for calculating the thyroid doses due to ^{131}I intake for the Belarusian-American cohort members. Briefly, doses were calculated in two steps using measurements of exposure rates near the thyroid and personal interviews, which were specific to each study subject, and ecological data (e.g., ^{131}I ground deposition in the settlements). At the first step, the so-called 'ecological' dose was calculated using ecological and biokinetic models that describe the transfer of ^{131}I through the chain 'ground deposition' → 'vegetation' → 'milk, milk products' → 'child's thyroid'. Information obtained from interviews about the residential history and consumption of milk, milk products, and leafy vegetables determined the modelled amount and variation over time of ^{131}I intake. One of the important

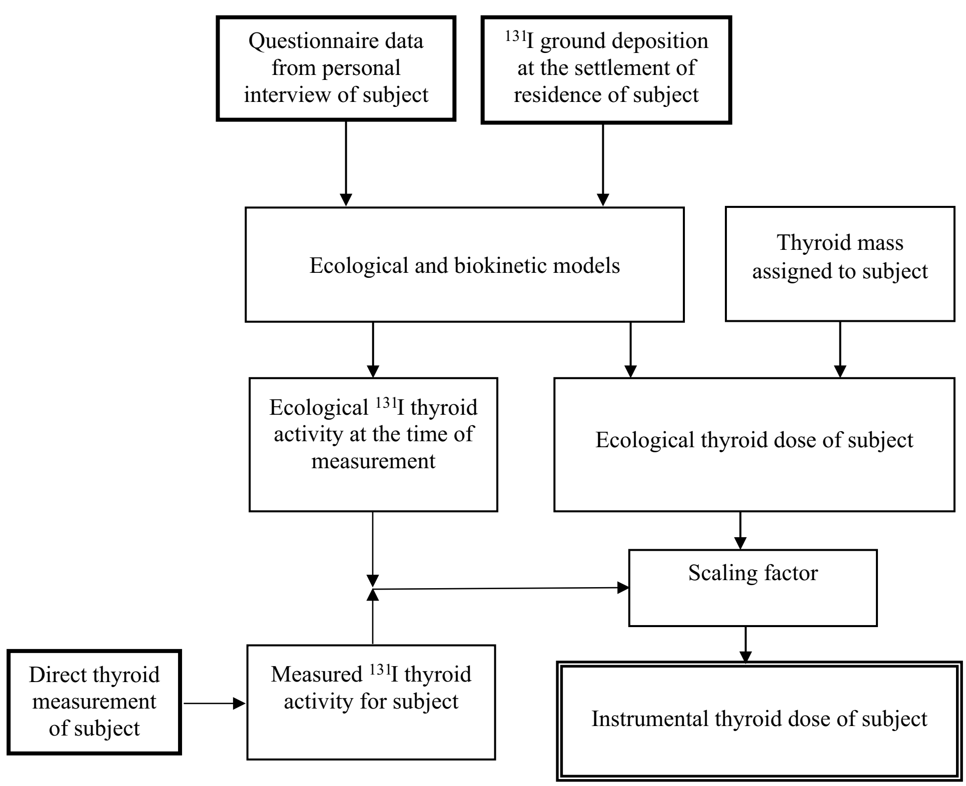

Fig. 1 Schema of thyroid dose calculation for the Belarusian-American cohort members

parameters for the analysis was the so-called 'scaling factor' that was defined as the ratio of the measured ^{131}I activity in the thyroid to the calculated ecological ^{131}I activity in the thyroid at the time of measurement. The scaling factor integrates steps in thyroid dose estimation, including ecological and biokinetic modeling and questionnaire data, and is a model setting that adjusts the individual thyroid dose. The scaling factor is used as an indicator of the credibility of dose modeling. If the scaling factor is less than 1, the ecological ^{131}I activity in the thyroid burden is overestimated in comparison with the measured ^{131}I activity in the thyroid.

In the second step, the ecologically estimated dose was adjusted using a scaling factor and the 'instrumental' thyroid dose was obtained using the following equation:

$$D_{\text{inst}} = \frac{Q_{\text{meas}}(t_m)}{Q_{\text{ecol}}(t_m)} \cdot D_{\text{ecol}} = SF \cdot D_{\text{ecol}} \quad (1)$$

where $Q_{\text{meas}}(t_m)$ is the activity of ^{131}I measured in the thyroid (kBq); $Q_{\text{ecol}}(t_m)$ is the ecological activity of ^{131}I in the thyroid at the time of measurement, t_m (kBq); SF is the scaling factor (unitless).

A detailed description of the calculation of ecological and instrumental thyroid doses can be found elsewhere (Drozdovitch et al. 2013).

The ecological dose was evaluated in the present study because it was used to determine the instrumental dose. For this purpose, ^{131}I activity concentrations in cow's milk produced in different locations in the most contaminated Gomel and Mogilev Oblasts were used (Minenko et al. 2020). The impact of individual information obtained by means of personal interviews with the cohort members or with their relatives on the ecological dose was also assessed. For this, the same measured ^{131}I activity in the thyroid and the same parameter values for the ecological and biokinetic models were used, to calculate the thyroid doses for each study subject; the only differences were those related to residential history, food consumption, and date of iodine prophylaxis; these data were taken from different questionnaires available for the same person.

^{131}I activity in milk

Consumption of fresh cow's milk and dairy products was the main source of ^{131}I intake for most study subjects. Therefore, it was important to assess how adequate the applied ecological model described the ^{131}I activity concentration in the chain 'ground deposition' → 'vegetation' → 'cow's milk'. For this, the ^{131}I activity concentration in cow's milk calculated using the ecological model was compared with ^{131}I activity concentrations measured in cow's milk produced in the same settlements (where the studied individuals came from) during the first month after the accident (Minenko et al. 2020). Table 2 compares measured ^{131}I activity concentrations in cow's milk normalized to 10 May 1986 with those calculated using the ecological model for those 38 settlements in which the study subjects lived at the time of the accident.

Study questionnaire and personal interview

A detailed description of the study questionnaire can be found elsewhere (Drozdovitch et al. 2013, 2016). In brief, the following information was collected for each study subject during a personal interview:

- Place of residence ATA, and, if applicable, places of residence between 26 April and 30 June 1986, and dates of residence;
- Origin, dates of consumption and consumption rates of cow's milk, milk products, and leafy vegetables between 26 April and 30 June 1986; and
- Dates of stable iodine administration between 26 April and 31 May 1986.

The information collected during the personal interview was saved in a specially designed database for further analysis and calculation of doses. The technique of double key entry of each questionnaire by two operators was used to create the database. Quality control of the two databases was done by comparison of the responses that were entered by the two operators. If discrepancies were found, the correct answer was checked in the paper questionnaire and the error was corrected in the database.

Table 3 shows the number of questionnaires available for the study subjects. A total of 336 questionnaires were available, including 168 questionnaires delivered during each of the screening: from 30 December 1996 through 31 March 2001 (first screening) and from 1 April 2001 through 31 May 2007 (second screening).

The quality of the data reported during the personal interviews depended on whether the respondents were the studied subject, the mother or other relatives, i.e. father, grandparents or siblings (Drozdovitch et al. 2016). A mother could provide the most reliable information about her child's behavior and nutrition that was typical 10–20 years earlier in early childhood (Burrows et al. 2010). In the present study, questionnaires were distributed to 199 mothers (59.2% of the total), 98 studied individuals (29.2%), and 39 other relatives (11.6%). It should be noted that the data in the questionnaires distributed to mothers were mainly used (109 out of 131, 83.2% of the total) to calculate the thyroid doses of the study subjects (Drozdovitch et al. 2013).

Table 2 List of 38 settlements of residence where the study subjects lived at the time of the accident, and where ^{131}I activity concentration in cow's milk was measured

District	Settlement	^{131}I activity concentration in cow's milk (kBq L^{-1}) normalized to 10 May 1986		Ratio of measured to calculated ^{131}I activity concentration in cow's milk
		Measured	Calculated using ecological model	
Bragin	Bragin-town	47	106	0.44
Bragin	Glukhovichi	3.5	98	0.036
Bragin	Ivanki	6.6	63	0.10
Bragin	Mariton	17	81	0.21
Bragin	Mikhnovka	40	71	0.56
Bragin	Ostroglyady	39	113	0.35
Bragin	Petritskoye	17	58	0.29
Bragin	Pirki	26	112	0.23
Bragin	Savichi	23	90	0.26
Bragin	Chikalovichi	9.1	67	0.14
Vetka	Svetilovichi	6.1	96	0.064
Vetka	Khizy	25	114	0.22
Vetka	Sherstin	6.0	88	0.068
Kalinkovichi	Ignatofabianovka	12	45	0.27
Mozyr	Mozyr-city	5.9	25	0.24
Narovlya	Antonov	28	92	0.30
Narovlya	Verbovichi	25	103	0.24
Narovlya	Grushevka	25	93	0.27
Narovlya	Dernovichi	32	112	0.28
Narovlya	Karpovichi	48	118	0.41
Narovlya	Narovlya-town	25	91	0.27
Rechitsa	Vyshemir	13	71	0.18
Rechitsa	Dukhanovka	0.84	63	0.013
Rechitsa	Novy Barsuk	19	59	0.32
Rechitsa	Perevoloka	0.72	58	0.012
Rechitsa	Rechitsa-city	7.2	38	0.19
Rechitsa	Semenovka	17	64	0.27
Rechitsa	Yanovka	8.0	52	0.15
Khoiniki	Babchin	20	114	0.18
Khoiniki	Veletin	16	89	0.18
Khoiniki	Veliky Bor	40	53	0.75
Khoiniki	Mokish	86	107	0.80
Khoiniki	Orevichi	109	135	0.81
Khoiniki	Pogonnoe	18	134	0.13
Khoiniki	Poselichi	53	95	0.56
Khoiniki	Strelichivo	40	91	0.44
Khoiniki	Tulgovichi	29	102	0.28
Khoiniki	Khoiniki-town	50	62	0.81

Direct thyroid measurements

In Belarus, direct thyroid measurements were performed using different types of radiation monitoring devices: the dose-rate meter DP-5, the survey meter SRP-68-01, and the dosimeter DRG3-02. These devices were not designed, however, to measure ^{131}I activity in the human thyroid. The errors associated with the ^{131}I thyroidal activity measured with the SRP-68-01 were evaluated in detail by Khrutchinsky et al. (2012). Similar evaluations were also done for the DP-5 and the DRG3-02 devices. Special studies were conducted in the Belarusian-American cohort to derive the ^{131}I content in the thyroid from the results of direct thyroid measurements (Drozdovitch et al. 2013, 2019; Kutsen et al.

Table 3 Number of individual questionnaires available

Number of questionnaires per person	Number of questionnaires completed during		Number of subjects	% of the total
	First screening	Second screening		
1	3	4	7	5.3
2	65	61	63	48.1
3	63	78	47	35.9
4	23	17	10	7.6
5	9	6	3	2.3
6	–	–	–	–
7	5	2	1	0.8
Entire study	168	168	131	100.0

2019). These studies allowed to correct the detector signals for signals from background radiation in the room, where the measurements had been made, and for signals from external surface contamination of the body and clothes as well as from internal contamination of the body with radiocesium isotopes, namely ^{134}Cs, ^{136}Cs, and ^{137}Cs.

Table 4 shows the distribution of the study subjects by type of radiation monitoring device. Seventy-three out of 131 persons (55.7% of the total) were measured using the SRP-68-01 device. Direct thyroid measurements among study subjects were conducted between 11 May and 17 June 1986. Most of the subjects, 116 out of 131 (88.6% of the total), were measured before 1 June 1986.

Evaluation of reliability of thyroid doses

The relative range of the scaling factors (expressed as the ratio of maximal to minimal scaling factor obtained for instrumental thyroid doses calculated for the same subject using information from different questionnaires) was calculated for each subject. A range of scaling factors could not be calculated, if only one personal interview was conducted for a subject and, therefore, only one value of the instrumental thyroid dose was available. Previous analyses of the scaling factors for the Belarusian-American cohort showed that scaling factor-values of more than 50 (note that a value of 1 would mean the perfect agreement between the ecological and measured ^{131}I thyroid activity) mean that thyroid doses are potentially suspicious (Drozdovitch et al. 2016). As it was noted above, the scaling factor can be interpreted as an indicator of the agreement between the ecological and instrumental thyroid doses. Previous analysis done for the entire Belarusian-American cohort showed that for 99.5% cohort members the ratio of instrumental doses calculated using different questionnaires did not exceed a factor of 3.0 (Drozdovitch et al. 2016). Therefore, if the ratio of maximal to minimal instrumental doses calculated using different questionnaires for the same individual was more than 3.0, the result of dose calculation for the study subject was potentially dubious.

With the exception of typing errors or assignment of the results of direct thyroid measurements to the wrong subject, the most possible explanation for extreme deviations is that the subject or his or her relatives provided incorrect answers during the personal interview (Drozdovitch et al. 2013). Therefore, information on the residential history, consumption rates of milk, dairy products, and leafy vegetables as well as on the dates of iodine prophylaxis, which was collected during several personal interviews for the same subject, was analyzed for internal consistency.

Results and discussion

Figure 2 compares ecological and measured ^{131}I activity concentrations in cow's milk normalized to 10 May 1986 for 38 settlements where the study subjects lived at the time of the accident. For all settlements, the ecological ^{131}I activity concentrations in cow's milk are higher than those actually measured. The ratio of the measured to calculated ^{131}I activity concentration in cow's milk ranged from 0.012 to 0.81 (Table 2). This demonstrates that the ecological model provides conservative estimates of ^{131}I activity concentrations in cow's milk and, consequently, of ^{131}I thyroid activity. Consequently, since consumption of milk and dairy products was the main source of ^{131}I intake for most of the study subjects, the ecological ^{131}I activity

Table 4 Distribution of the study subjects by type of radiation monitoring device used for direct thyroid measurements

Device	Method of measurement	Detector type	Number of measured persons	% of the total
DP-5	Exposure rate	Geiger-Mueller	55	42.0
SRP-68–01	Exposure rate	NaI(Tl), ∅30 mm	73	55.7
DRG3-02	Exposure rate	plastic scintillator	1	0.8
RFT-20046[a]	Spectrometry	NaI(Tl), ∅63 mm	2	1.5
Entire study			131	100.0

[a]One-channel gamma-spectrometer; measurements were done in Saint Petersburg (formerly Leningrad)

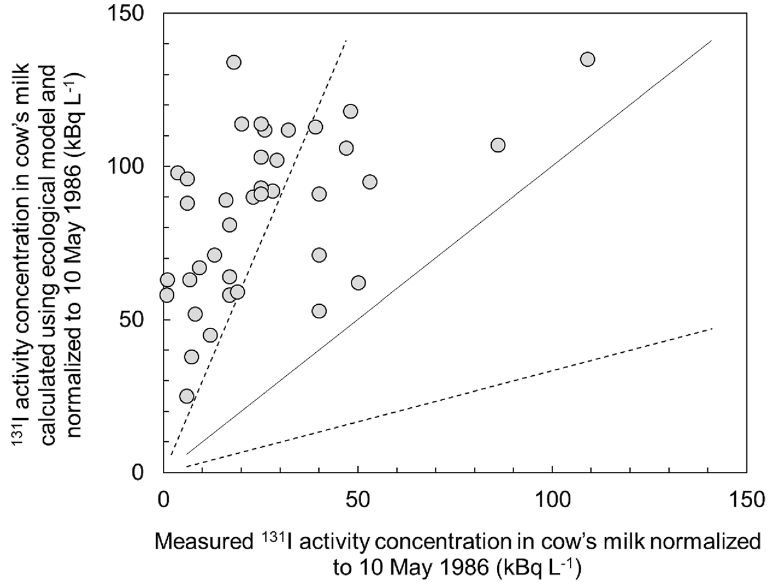

Fig. 2 Comparison of ecological and measured ^{131}I activity concentrations in cow's milk normalized to 10 May 1986 for 38 villages where the studied individuals lived at the time of the accident. Dashed lines show a factor of 3 difference between the two sets of ^{131}I activity concentrations in cow's milk

in the thyroid is expected to be higher than the measured ^{131}I activity. Therefore, the scaling factor is expected to be less than 1, as it is directly proportional to the ^{131}I activity concentrations in cow's milk:

$$SF = \frac{Q_{meas}(t_m)}{Q_{ecol}(t_m)} \sim \frac{I_{real}}{I_{ecol}} = \frac{A_{real}^{diet} \cdot V_{real}^{diet}}{A_{ecol}^{diet} \cdot V_{quest}^{diet}} \tag{2}$$

where I_{real} is the realistic daily intake of ^{131}I activity with cow's milk and other foodstuffs that determined the measured ^{131}I thyroid activity (kBq d^{-1}); I_{ecol} is the intake of ^{131}I activity with cow's milk and other foodstuffs that were calculated using the ecological model (kBq d^{-1}); A_{real}^{diet} and A_{ecol}^{diet} are the realistic and ecological ^{131}I activity concentrations in diet normalized to 10 May 1986, respectively (kBq L(kg)$^{-1}$); V_{real}^{diet} and V_{quest}^{diet} are the realistic daily food consumption and that reported by the individuals in the questionnaires, respectively (L(kg) d^{-1}).

Interestingly, in this study, the scaling factor was greater than 1 for 117 out of 131 (89.3% of the total) study subjects. According to Eq. (2), the scaling factor-values include the consumption rates reported in the personal questionnaire. Therefore, even with a conservative estimate of the ^{131}I activity concentration in the diet (see Table 2 for cow's milk), the total ^{131}I intake can be underestimated due to incorrect information on the quantitative and qualitative composition of the diet of an investigated individual. The use of information from repeated interviews to calculate ecological thyroid doses for the same subject showed that the differences between the scaling factor-values for the same study subjects could reach 2–3 orders of magnitude, if different information on consumption habits was provided during repeated interviews (see data for the subjects *B*, *D* and *F* in Table 6 below).

Figure 3 shows the instrumental thyroid doses due to ^{131}I intake for the 20 most exposed members of the Belarusian–American cohort. Multiple circles for the same cohort member represent thyroid doses calculated using information from different questionnaires. For most subjects, there is reasonable agreement between the thyroid doses calculated using different questionnaires. The degree of agreement for all 131 study subjects is shown in Table 5 as the distribution of the ratio of maximal to minimal doses calculated for the same subject using information from different questionnaires. For 63 of the 131 study subjects (50.8% of the total) with thyroid doses of more than 5 Gy, doses calculated for the same person but using information from different questionnaires agreed within a factor of 1.3, while for 112 subjects (90.3% of the total) they agreed within a factor of 2.

Figure 4 shows the ratio of ecological thyroid doses corresponding to maximal and minimal scaling factor-values *vs.* the ratio of maximal to minimal scaling factor-values. Figure 5 shows the same relationship for the instrumental thyroid doses. Although for most of the subjects an agreement between the analyzed values is observed, there are several outliers, which indicate subjects with potentially suspicious thyroid doses. The possible reasons for this were identified by Drozdovitch et al. (2013, 2016) to be (i) typing error during recording the results of measurements, (ii) assignment of the result of a direct thyroid measurement to a wrong person (e.g., for persons with the same last name and/or initials), or (iii) incorrect answer during a personal interview.

As it was mentioned above, the following criteria were used to identify the subjects with potentially suspicious thyroid doses:

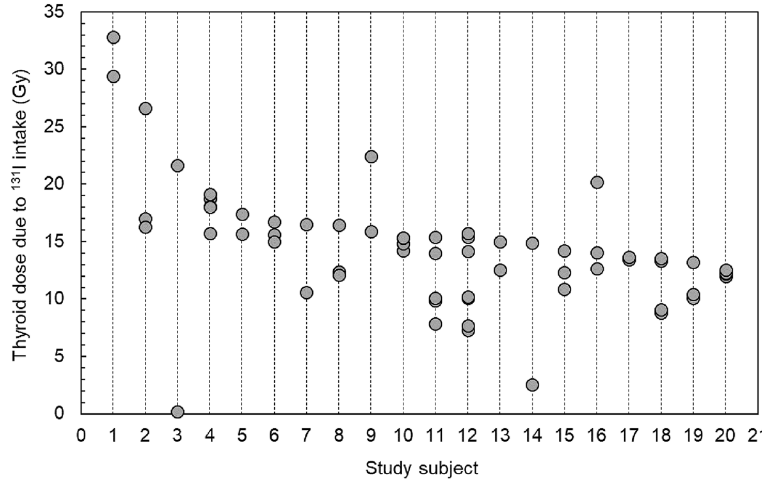

Fig. 3 Instrumental thyroid doses due to ^{131}I intake for the 20 most exposed members of the Belarusian-American cohort. Several circles for the same cohort members represent thyroid doses calculated using information from different questionnaires

Table 5 Distribution of the ratio of the maximal to minimal instrumental thyroid doses obtained for the same subject using information from different questionnaires

Range of the ratio of the maximal-to-minimal thyroid doses	Number of persons	% of the total
1.0–1.09	24	19.4
1.1–1.29	39	31.4
1.3–1.49	18	14.5
1.5–1.99	31	25.0
2.0–2.99	9	7.3
3.0–4.99	1	0.8
5.0–9.99	1	0.8
10.0+	1	0.8
Entire study	124[a]	100.0

[a]Total number of subjects is not equal to 131 as seven persons were interviewed only once

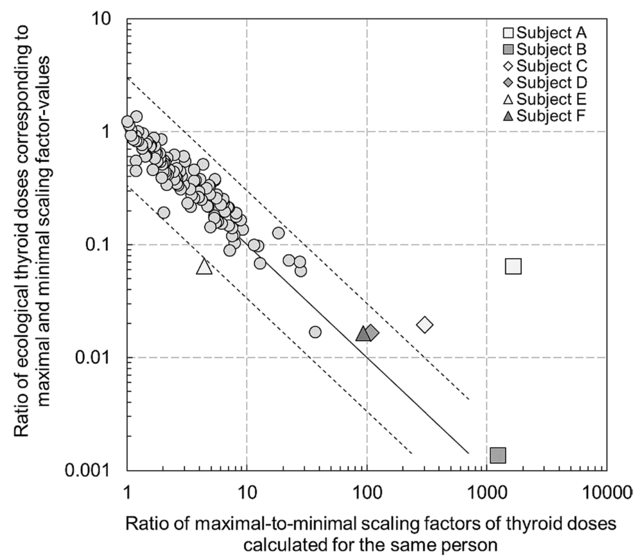

Fig. 4 Ratio of ecological thyroid doses corresponding to maximal and minimal scaling factor-values *vs.* the ratio of maximal to minimal scaling factor-values obtained for thyroid doses calculated for the same subject using information from different questionnaires. Dashed lines show a factor of 3 difference between the two sets of ratios

- The ratio of maximal to minimal scaling factor-values for thyroid doses calculated for the same subject using information from different questionnaires is over 50; or
- The ratio of instrumental thyroid doses corresponding to maximal and minimal scaling factor-values is smaller than 0.33 or greater than 3.0.

Based on the available information, the following subjects with potentially suspicious thyroid doses were selected (Figs. 4 and 5):

- Four subjects (*A*, *B*, *C,* and *D*) with a ratio of maximal to minimal scaling factors greater than 100, calculated for the same subject using information from different questionnaires over 100;
- One subject (subject *E*) with a ratio of instrumental thyroid doses corresponding to maximal and minimal scaling factor-values of 0.28 (i.e., less than 0.33); and
- One study subject (subject *F*) with a ratio of maximal to minimal scaling factors of 87, which is between 50 and 100.

Among the seven study subjects for whom only one personal interview was conducted, the scaling factor ranged from 1 to 375. Thyroid dose for a subject with a scaling factor of 375 was potentially suspicious (subject *J*) (not shown on the figures). The median scaling factor-value among the remaining six persons was 2.6 (range 1.0–35) indicating reasonable agreement between ecological and instrumental thyroid doses: This confirmed the reliability of instrumental dose estimates for these individuals.

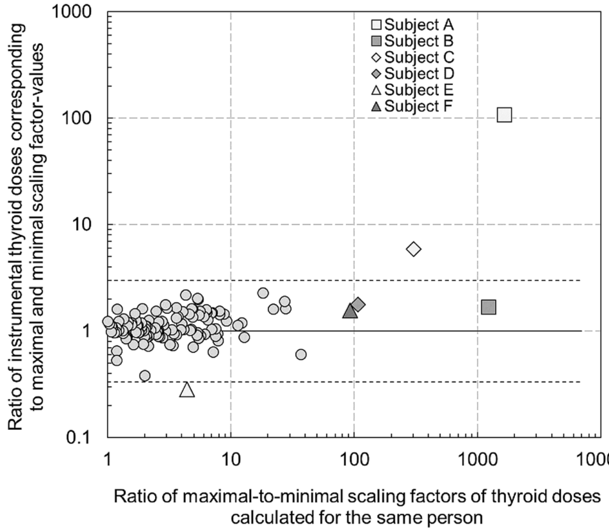

Fig. 5 Ratio of instrumental thyroid doses corresponding to maximal and minimal scaling factor-values *vs.* the ratio of maximal to minimal scaling factor-values obtained for thyroid doses calculated for the same subject using information from different questionnaires. Dashed line shows a factor of 3 difference between the two sets of ratios

Table 6 shows the characteristics of direct thyroid measurements, data on residential history and consumption habits prior to the date of thyroid measurement, based on information from different questionnaires, scaling factors, and thyroid dose estimates for the seven study subjects with potentially suspicious thyroid doses.

Study subject A

The following discrepancies were observed in the data from two personal interviews conducted with the study subject on 21 October 1999 and with her mother on 12 September 2001: according to the first interview, the subject permanently resided in Khoiniki raion, while according to the second interview she moved to the non-contaminated Orsha raion on 26 April 1986. The place of residence at the date of direct thyroid measurement reported during the second interview agrees with the location of measurement. However, it was impossible to accumulate a ^{131}I thyroid activity of 11 kBq as measured on 9 May 1986 in the non-contaminated Orsha raion during the period from 26 April to 9 May 1986. The ecological ^{131}I thyroid activity at the time of measurement was calculated to be 0.084 kBq and the scaling factor was 130. It was concluded that the result of the thyroid measurement was assigned to the study subject by mistake and, therefore, the instrumental thyroid dose for the subject cannot be correctly estimated.

Study subject B

Four questionnaires were available for this subject. The place of residence at the date of thyroid measurement reported during all interviews agrees with the place of measurement. The information on the residential history and consumption rates reported during all personal interviews (except for the first one) is reasonably consistent. Instrumental thyroid doses calculated using the information in the four available questionnaires agree reasonably well within a factor of 1.7, while the scaling factors agree within a factor of 3.3 (again except for questionnaire #1). Although, the ecological thyroid dose calculated using questionnaire #1 was almost 3 orders of magnitude lower than that calculated using the other questionnaires and, accordingly, the scaling factor was almost 3 orders of magnitude higher, the instrumental thyroid dose calculated using questionnaire #1 agreed with the scaling factors calculated using the other questionnaires (Table 6). It is concluded that the dose estimates for this subject are consistent and reliable.

Study subject C

This subject, who was 12.9 years old ATA, was interviewed twice. According to the first interview, the subject relocated to Gomel on 27 April 1986 (before the date of major fallout), while according to the second interview the subject relocated to Minsk on the same day. The place of residence at the date of the direct thyroid measurement reported during the first interview agrees with the location of measurement. The thyroid ^{131}I activity of 380 kBq measured on 12 May 1986 matches the ecological ^{131}I thyroidal activity calculated using the information given in questionnaire #1 (scaling factor equals to 9.7), while the scaling factor calculated based on questionnaire #2 was 2,900. Because the residential history and dietary information obtained during the second interview inadequately describe the measured ^{131}I thyroid activity, and because the locations of measurement and residence do not match, it is concluded that the result of thyroid measurement could have been mistakenly assigned to the study subject. Therefore, the thyroid dose for the subject cannot be correctly estimated.

Study subject D

The subject was 0.3 years old ATA, and her mother was interviewed twice. According to the first interview, the subject moved to the city of Mozyr on 9 May 1986, while according to the second interview, the relocation occurred on 30 April 1986. The place of residence at the date of thyroid measurement given in both interviews agrees with the location of measurement. The thyroid ^{131}I activity of 47 kBq measured on 13 May 1986 matches the ecological

Table 6 Characteristics of direct thyroid measurements, data on residential history and consumption habits obtained from different questionnaires, and thyroid dose estimates for seven study subjects with potentially suspicious doses

Parameter	Study subject *A*		Study subject *B*			
Age at time of the accident (years)	3.3		7.3			
Gender	F		M			
Date of measurement	9 May 1986		23 May 1986			
Place or raion of measurement	Orsha		Gomel			
Measurement device	SRP-68–01		SRP-68–01			
Measured ^{131}I thyroid activity (kBq)	11		130			
Questionnaire	#1	#2	#1	#2	#3	#4
Date of interview	21 Oct 1999	12 Sep 2001	4 June 1998	15 Oct 1999	15 Aug 2001	22 May 2006
Respondent	Subject	Mother	Mother	Subject	Subject	Mother
Raion or city of residence ATA with	Khoiniki	Khoiniki	Gomel	Bragin	Bragin	Bragin
^{131}I deposition density[a] (MBq m^{-2})	1.3	1.3	0.63	21	21	21
Date of moving	–[b]	26 Apr 1986	–	4 May 1986	4 May 1986	4 May 1986
Raion or city of new residence with	–	Orsha	–	Gomel	Gomel	Gomel
^{131}I deposition density[a] (MBq m^{-2})	–	0.043	–	0.63	0.63	0.63
Consumption rate (L(kg) day^{-1})						
Cow's milk	0.45	0	0	1.0	1.4	1.0
Dairy products	0	0.029	0	0.68	0.30	0.20
Leafy vegetables	0.019	0.030	0	0	0.018	0.024
Date of stable iodine prophylaxis	–	–	–	–	–	3 May 1986
Ecological ^{131}I thyroid activity[c] (kBq)	140	0.084	0.21	130	240	73
Scaling factor	0.079	130	620	1.0	0.54	1.8
Thyroid dose due to ^{131}I intake (Gy)						
Ecological	2.4	0.15	0.010	4.8	7.7	3.1
Instrumental	0.19	20	6.2	4.8	4.2	5.6

Parameter	Study subject *C*		Study subject *D*		Study subject *E*	
Age at time of the accident (years)	12.9		0.3		1.7	
Gender	F		F		M	
Date of measurement	12 May 1986		13 May 1986		8 June 1986	
Place or raion of measurement	Gomel		Mozyr		Gomel	
Measurement device	DP-5		DP-5		DP-5	
Measured ^{131}I thyroid activity (kBq)	380		47		6.1	
Questionnaire	#1	#2	#1	#2	#1	#2
Date of interview	14 Mar 2000	24 May 2001	14 Apr 1999	17 Apr 2003	10 May 1999	8 Dec 2005
Respondent	subject	subject	mother	mother	subject	other relative
Raion or city of residence ATA with	Bragin	Bragin	Narovlya	Narovlya	Khoiniki	Khoiniki
^{131}I deposition density[a] (MBq m^{-2})	12	12	11	11	160	160
Date of moving	27 Apr 1986	27 Apr 1986	9 May 1986	30 Apr 1986	27 Apr 1986	3 May 1986
Raion or city of new residence with	Gomel	Minsk	Mozyr	Mozyr	Gomel	Gomel
^{131}I deposition density[a] (MBq m^{-2})	0.63	0.11	0.38	0.38	0.63	0.63
Consumption rate (L(kg) day^{-1})						
Cow's milk	0.03	0	1.2	0.20	0	0.50
Dairy products	0.14	0.018	0.11	0	0.23	0
Leafy vegetables	0	0	0	0	0	0
Date of stable iodine prophylaxis	–	5 May 1986	–	–	27 Apr 1986	–
Ecological ^{131}I thyroid activity[c] (kBq)	39	0.13	267	2.6	2.6	11
Scaling factor	9.7	2,900	0.18	18	2.3	0.55
Thyroid dose due to ^{131}I intake (Gy)						
Ecological	0.27	0.0052	18	0.31	0.66	10

Table 6 (continued)

Parameter	Study subject *C*		Study subject *D*		Study subject *E*	
Instrumental	2.6	15	3.2	5.6	1.5	5.5
Parameter	**Study subject *F***					**Study subject *J***
Age at time of the accident (years)	0.7					7.2
Gender	M					M
Date of measurement	23 May 1986					4 May 1986
Place or raion of measurement	Gomel					Minsk
Measurement device	DP-5					SRP-68–01
Measured ^{131}I thyroid activity (kBq)	22					60
Questionnaire	#1	#2	#3	#4	#5	#1
Date of interview	15 Dec 1997	21 Dec 1998	31 May 1999	29 Nov 2001	25 Sep 2002	15 May 2006
Respondent	Mother	Mother	Mother	Mother	Mother	Mother
Raion or city of residence ATA with	Bragin	Bragin	Bragin	Bragin	Bragin	Minsk
^{131}I deposition density[a] (MBq m^{-2})	9.7	9.7	9.7	9.7	9.7	0.11
Date of moving	3 May 1986	3 May 1986	30 Apr 1986	3 May 1986	5 May 1986	–[d]
Raion or city of new residence with	Gomel	Gomel	Gomel	Gomel	Gomel	–
^{131}I deposition density[a] (MBq m^{-2})	0.45	0.45	0.45	0.45	0.45	–
Consumption rate (L(kg) day^{-1}):						
Cow's milk	0.10	0.70	0	0.75	0.40	0.13
Dairy products	0.25	0.20	0	0.19	0.23	0.10
Leafy vegetables	0.003	0.005	0	0	0	0
Date of stable iodine prophylaxis	–	–	–	–	–	–
Ecological ^{131}I thyroid activity[c] (kBq)	13	30	0.38	33	24	0.16
Scaling factor	1.7	0.73	58	0.67	0.92	375
Thyroid dose due to ^{131}I intake (Gy):						
Ecological	2.5	7.6	0.15	8.6	5.8	0.017
Instrumental	4.3	5.6	8.7	5.8	5.3	6.4

ATA at the time of the accident

[a] ^{131}I deposition density is given for settlement of residence in raion of residence provided in the table

[b] Permanent residence in Khoiniki raion from the time of the accident until 30 June 1986

[c] At the time of thyroid measurement

[d] Permanent residence in the city of Minsk from the time of the accident until 30 June 1986

^{131}I thyroid activity calculated using questionnaire #1 (scaling factor equals to 0.18) and questionnaire #2 (scaling factor equals to 18). Although the ratio of maximal to minimal ecological thyroid doses is 60 and the ratio of scaling factor is 107, the ratio of instrumental thyroid doses was only 1.8. The data available for the subject reaffirmed an early observation that the instrumental dose was practically independent of the scaling factor-values, i.e. inconsistent information from the two personal interviews on consumption rates resulted in different ecological doses but did not affect the instrumental dose. It is concluded that the instrumental thyroid dose calculated for this subject is reliable.

Study subject E

The subject was 1.7 years old ATA and was interviewed twice. ATA, the subject resided in a highly contaminated settlement within the 30-km zone. He was evacuated to the city of Gomel on 27 April 1986 and on 3 May 1986 according to the first and second interviews, respectively. The place of residence at the date of the thyroid measurement reported during both interviews is the same as the place of measurement. Iodine-131 thyroid activity of 6.1 kBq measured on 8 June 1986 matches ^{131}I thyroid activity calculated using questionnaire #1 (2.6 kBq, scaling factor equal to 2.3) and questionnaire #2 (11 kBq, scaling factor 0.55). Although the difference between two the instrumental doses was a factor of 3.6, the scaling factor-values are distributed around 1.0, and, therefore, the instrumental thyroid doses (1.5 and 5.4 Gy) for the subject are considered consistent and reliable.

Study subject F

This subject was 0.7 years old ATA, and his mother was interviewed five times. The subject moved to Gomel raion, and different dates of relocation between 30 April and 5 May 1986 were reported during the interviews. The place of residence at the date of direct thyroid measurement reported during all interviews agrees with the place of measurement. The activity of ^{131}I in the thyroid of 22 kBq measured on 23 May 1986 corresponds to the ecological ^{131}I thyroid activity calculated using all questionnaires, except for questionnaire #3; the scaling factor ranges from 0.67 to 1.7 (again leaving out the third questionnaire). The ecological and instrumental thyroid doses calculated using all questionnaires, except for questionnaire #3, are consistent. Therefore, it is concluded that the instrumental thyroid doses for this subject are reliable.

Study subject J

Subject J was 7.2 years old ATA, and there was one questionnaire administered to his mother. Subject J has permanently resided in the city of Minsk since the time of the accident, where he underwent a thyroid measurement. However, the ^{131}I thyroid activity of 60 kBq measured on 4 May 1986 could not be accumulated when living in the low-contaminated city of Minsk. The ecological ^{131}I thyroid activity at the time of measurement was calculated to be 0.16 kBq, and the corresponding scaling factor was 375. It is concluded that the result of thyroid measurement was assigned to the subject by mistake and, therefore, the thyroid dose for this subject cannot be properly assessed.

An in-depth analysis of thyroid measurements, data on residential history and consumption habits obtained from different questionnaires, scaling factors, ecological and instrumental thyroid doses, was conducted in a similar manner for the other 124 study subjects included in the present study. It was found that the thyroid doses for these subjects are consistent and reliable. For the entire study, the instrumental thyroid doses due to ^{131}I intake exceeding 5 Gy were suspicious for three out of 131 study subjects (2.3% of the total).

The analysis showed that the ratio of maximal to minimal scaling factors for the subject was close to the ratio of maximal to minimal ecological thyroid doses when practically the same residential history, but different consumption rates were reported during different personal interviews. In such instances, even if the deduced scaling factors were up to 1,000, the instrumental thyroid doses calculated using information from the different questionnaires agreed reasonably well, that is for the study subjects *B*, *D* and *F* (see Figs. 4 and 5, and Table 6). However, if different residential histories were reported during the different personal interviews, e.g. residence in highly contaminated settlement vs. residence in a low contaminated settlement, the ecological thyroid doses, scaling factors and instrumental thyroid doses calculated using the information form the different questionnaires were found to be inconsistent (see data for the study subjects *A* and *C* in Figs. 4 and 5, and Table 6).

It should be noted that the approach used in this study did not allow to conclude directly whether a thyroid measurement was assigned to the right person or not. However, the availability of two or more questionnaires from repeated personal interviews allowed us to identify a potentially suspicious situation when the measurement was assigned to a person by mistake (see analysis for subjects *A* and *C*). Therefore, it is essential to conduct repeated interviews to validate dose estimates even if they are based on individual radiation measurements for the study subjects. In addition, even for a ratio of maximal to minimal scaling factors greater than 1,000, the instrumental thyroid doses calculated using information from different questionnaires were reasonably consistent (see analysis for subject *B*). To evaluate whether the measured ^{131}I thyroid activity correctly reflects the variation with time of ^{131}I intake, which was calculated using the residential history and consumption rates reported for the subject, multiple direct thyroid measurements done for the same subject should be analyzed. Unfortunately, such multiple measurements were not available for the vast majority of the Belarusian-American cohort members, and in particular not available for the individuals investigated in the present study.

The observed variability of the ratios of the scaling factor-values was much wider than the variability of the ratios of instrumental thyroid doses (Fig. 5). This is due to the fact that the scaling factor includes, in addition to information from measurements, the personal questionnaire data. Residential history and consumption rates could differ between interviews due to poor memory or because different respondents (subject, his or her mother, or other relatives) were interviewed at different points in time (Drozdovitch et al. 2016). However, the quality of individual dietary data has, in general, a small influence on the instrumental thyroid doses because there were results of thyroid measurements available for the study subjects (Fig. 5).

Shinkarev et al. (2008) evaluated the credibility of the Chernobyl thyroid doses exceeding 10 Gy in 331 out of 126,261 persons who underwent direct thyroid measurements in Belarus in April–June 1986. The overall conclusion of their study, “dose estimates exceeding 10 Gy based on direct thyroid measurements in Belarus are credible estimates and not mistakes”, supports the findings of the present study. However, the advantages of the present study compared with the study of Shinkarev et al. (2008) are (i) correction of thyroid detector signals for additional signals from background radiation in the room, where the measurements were done, from the external surface contamination of the body and contaminated clothes, and from internal contamination due to the presence of radiocesium isotopes in the body and (ii) availability of detailed information on the individual residential history, consumption habits and iodine prophylaxis which were obtained by means of the personal interviews (in many instances multiple) for each study subject.

It should be noted that although multiple-dose estimates were available in many instances for the same study subject, the instrumental thyroid dose calculated using the last questionnaire was included in the epidemiologic analysis as required by the study design.

The calculations of the thyroid doses using information from several questionnaires were done here in the framework of a deterministic model, since the simulation of individual stochastic doses by means of Monte Carlo methods would have required a significant amount of computer time. However, Drozdovitch et al. (2015) showed reasonable agreement between deterministic doses and arithmetic means of 1,000 individual stochastic doses. Therefore, the findings and results of the present study also apply to individual stochastic doses.

Conclusions

This paper provides an assessment of the reliability of thyroid doses due to ^{131}I intake estimated to be greater than 5 Gy, for 131 members of the Belarusian-American cohort. A reliability assessment was done by analyzing questionnaire data, the results of ecological and instrumental thyroid dose estimates, and associated scaling factors calculated for the same subjects using the data from the questionnaires distributed at different points in time. The instrumental thyroid doses due to ^{131}I intake were found to be suspicious for three out of 131 study subjects (2.3% of the total) where the thyroid measurement was obviously mistakenly assigned to the study subject during cohort construction. The present study confirmed that for the vast majority of the Belarusian-American cohort members, thyroid dose estimates due to ^{131}I intake exceeding 5 Gy are reliable and suitable for use in epidemiological analysis.

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Conflict of interest The authors declare that this work was carried out in the absence of any personal, professional or financial relationships that could potentially be construed as a conflict of interest.

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