Thyroid dose and thyroid cancer incidence after the Chernobyl accident: assessment for the Bryansk region of Russia

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This paper describes the method for reconstruction of the dose of internal irradiation of thyroid with incorporated ^{131}I. It is based on a statistical relationship between the mean internal dose estimated from individual thyroid radiometry and contamination around the population point. Using the method estimates of mean thyroid dose from incorporated ^{131}I were derived as a function of age for each population point of the Bryansk region, along with estimates of collective thyroid dose for all 27 administration districts of the region. For example, for 1.473 million residents of the Bryansk region living in 3,085 population points the collective thyroid dose is estimated at 34,200 people Gy. The largest contribution to the collective dose is made by Klintsovsky (35.3%), Krasnogorsky (22%) and Novozybkovsky (13.1%) districts of the Bryansk region. The obtained results were used in the search of dose relationship of thyroid incidence rate among children and adolescents of 0-17 years at the time of the Chernobyl accident living in the Bryansk region of RF. The analysis is based on 68 cases (47 girls and 21 boys) diagnosed in the assumed post-latent period from 1991 to 1996. The total population of the Bryansk region of 0-17 years at the time of the accident was about 375 thousand persons. The statistically significant estimate of the excess absolute risk for boys was estimated to be 1.5 (0.0, 2.8 - 95% confidence interval (CI)) [10^4 person years Gy]$^{-1}$; for girls - 2.0 (0.5, 3.5 - 95% CI) [10^4 person years Gy]$^{-1}$. The excess relative risk per 1 Gy is 12.7 (0.3, 24.5) and 6.5 (1.6, 11.2), respectively. It has been demonstrated that for the period from 1986 to 1990 the detectability of spontaneous thyroid cancers increased by a factor of 5-8 due to the effect of screening.

Introduction

It is common knowledge that irradiation of thyroid can cause an increase in the incidence of thyroid malignant neoplasms. The radiation risks of the induction of thyroid cancer are among the highest [1-3]. The minimum latent period of development of this disease is about 5 years.

The radiation risk of thyroid cancer morbidity is largely dependent on age at exposure and increases with the decrease in age [1-3]. In case of thyroid exposure to incorporated iodine radionuclides this relationship becomes even more pronounced, as the absorbed thyroid dose is also dependent on age. Data on risk coefficients quoted in [1, 2] primarily apply to external irradiation of thyroid. The risk coefficients for the cases of internal irradiation of thyroid with incorporated iodine radionuclides have been derived using a limited number of cases and therefore have a considerable uncertainty [1-4].

As a consequence of the Chernobyl accident the thyroid of many people was subject to internal irradiation with incorporated iodine radionuclides, primarily ^{131}I.

The many-years follow-up of the people living in the areas of the former USSR contaminated after the Chernobyl accident suggests that the worst negative health effects are associated with internal thyroid exposure to incorporated radio iodine [5-8]. In Russia the increased thyroid cancer incidence was discovered among children and adolescents living in the Bryansk region at the time of the accident, which was exposed to the highest contamination.

The conventional epidemiological approach to analysis of thyroid cancer incidence is based on estimation of collective population dose and comparison of observed incidence and that predicted by collective dose and risk factors recommended by ICRP. This method is well represented by the study [9] performed for the residents of the Bryansk region and identifying the most contaminated areas in it. Later the authors refined the collective thyroid dose [10] using the earlier assumptions and approximations.

A radically different approach to reconstruction of absorbed internal thyroid doses for the residents of the Bryansk region has been published in [11] based on results of individual thyroid measurements for residents of the Belarus and some districts in the Kaluga and Bryansk regions of Russia. Collective thyroid doses for the residents of the Bryansk region have also been estimated in [12] with experimental data and modeling calculations of the dynamics of ^{131}I milk contamination. This estimate is an order of magnitude higher the one given in [10] and seems to be the most conservative. It is based on activity measurements of milk produced in May-June 1986 in all areas of the Bryansk region. These results indicate that ^{131}I milk contamination was considerable even in the areas with low ^{137}Cs soil contamination density. After publication this should be thoroughly analyzed.

In work [13] we examined the methodology and results of individual thyroid activity measurements conducted in the Bryansk cancer dispensary in May-June 1986 and estimated absorbed thyroid doses based on these measurements. We have not found any good correlation between average thyroid doses in different age groups and average ^{137}Cs contamination density in a settlement, as was done in [9]. The reconstruction of thyroid doses is made even more difficult by the fact that in the Bryansk region only 1,000 measurements of thyroid incorporated ^{131}I activity were made professionally. The rest 13000 measurements reported in [8] had much lower accuracy and reliability. Of them about 1000 measurements were available to us.

Using these data we developed a different method for reconstructing thyroid dose due to incorporated ^{131}I. This method involves a search for a statistical correlation between the average internal dose and average ^{131}I contamination density. Using it we estimated the collective thyroid dose for the 27 administrative districts of the Bryansk region and this made possible to study explicitly the dose dependence of thyroid cancer incidence among children and adolescents (at the time of the accident) living in the Bryansk region in 1986. Similar relationship has been established in work [8] for thyroid cancer incidence among the population of Ukraine, Belarus and Bryansk region of RF, but these results are not conclusive enough because of the differing quality of primary data of thyroid dose measurements in different republics of CIS and different methods used for dose reconstruction.

In our estimation of the risk coefficients (excess absolute EAR and excess relative ERR) we used 68 cases of thyroid cancer diagnosed in the Bryansk region of RF among children and adolescents (0-17 years inclusive at the time of the Chernobyl accident) after the assumed latent period from 1991 to 1996.

Radio ecological situation in the Bryansk region after the Chernobyl accident

The radiation situation in the territory of the Bryansk region after 26 April 1986 was mainly attributed to radionuclides deposited on the ground after the accident. The contamination mostly occurred within one day since mid-day 28 April 1986 as a result of radionuclides release from the 4th unit of the Chernobyl NPP in the time interval from 18 o'clock on 27 April to 12 o'clock on 28 April 1986 [14]. The southwest areas of the region were under the radioactive cloud from 13 o'clock on 28 April to 7 o'clock on 29 April 1986. The cloud was moving eastward and left the territory of the Bryansk region at about 20 o'clock on 29 April 1986.

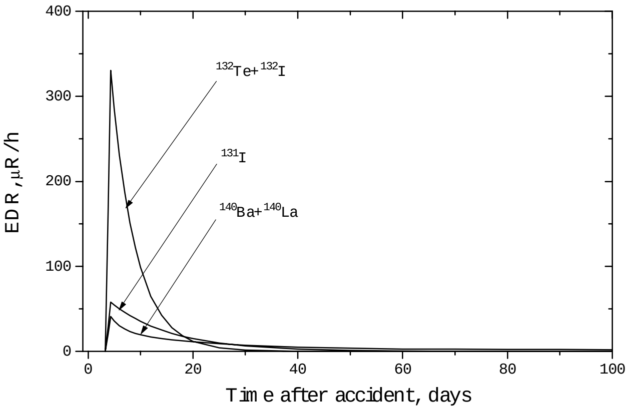
After passing over the southern and western areas of the Bryansk region the radioactive cloud was moving towards Tula, its edge covering the southern areas of the Kaluga region. Practically all the period when the cloud was passing over the Bryansk region it was raining at the intensity of 0.05 to 10 mm/h. The precipitation has led to the washout of the radioactive particles from the cloud enhancing the sedimentation rate of radionuclides. As it was the precipitation that was responsible for the spotty character of the contamination in the region.

The radioactive cloud contained a large amount of γ- and β-emitting radionuclides with different half-lives in the gaseous (^{131}I and ^{133}I) and aerosol forms. Of them the most long-lived was ^{137}Cs. The radionuclides with half-life of about a month and less virtually decayed in the first year after the accident. For the 5-7 years since April 1987 an important role, besides ^{137}Cs, was also played by ^{134}Cs. The contribution of ^{134}Cs with time was decreasing in accordance with the law of radioactive decay. At present the radiation situation in the Bryansk region is fully determined by ^{137}Cs contamination of soil and other environmental matrices. The radioactive composition of depositions in the region varies as a function of the distance to ChNPP [14].

The integral characteristic of radioactive depositions, which eventually determines population external doses, is the exposure dose rate (EDR). Figure 1 shows results of study [14] on dose rate reconstruction in a simplified form for key radionuclides deposited on the ground, given the ^{137}Cs contamination density of 37 kBq/m^2. As can be seen from Figure 1 during the first 20 days after the accident the major input to dose rate was made by the following radionuclides: ^{132}Te+^{132}I, ^{140}Ba+^{140}La. Later on (up to 100 days) significant contribution was made by ^{137}Cs+^{137m}Ba, ^{134}Cs and ^{103}Ru+^{103m}Rh. Of minor importance for formation of dose rate in the contaminated settlements were soil depositions of ^{136}Cs and ^{133}I (during several days after the accident).

In 2,320 settlements in the contaminated area of the Bryansk region specialists of SPA «Typhoon» of Roshydromet collected soil samples in which ^{137}Cs was measured [15]. By the beginning of 1995 the largest number of samples were collected in Klintsy (295) and Uvelie, Uvelie village soviet (345) and Zaborie, Zaborie village soviet, Krasnogorsky district (421). In 291 settlements ^{137}Cs soil contamination density was measured in one sample only. In 1,397 settlements by the beginning 1995 not more than 9 samples were collected (63% of 2,320 settlements). This demonstrates incompleteness and inaccuracy of data on radioactive contamination of the region today. To extend the source data, using the geo information system RECASS [16] developed by SPA «Typhoon» we generated a smooth interpolation ^{137}Cs contamination field for the Bryansk region by average, minimum and maximum values for 2,320 settlements. For the rest 855 points with the population of 163 thousand people, by the data of 1989 census, the ^{137}Cs contamination density was reconstructed by interpolation with geographical coordinates.

Thus we estimated that as of the indicated time there were 3,085 settlements in the ^{137}Cs contamination area with the average contamination density of more than 3.7 kBq/m^2 (0.1 Ci/km^2) referred to the date of deposition start (this condition will be used everywhere; the ^{137}Cs soil contamination density due to global fall-out as result of nuclear tests is close to 1.9 kBq/m^2). Table 1 shows distribution of settlements in the Bryansk region by the number of soil samples in which ^{137}Cs activity was measured.



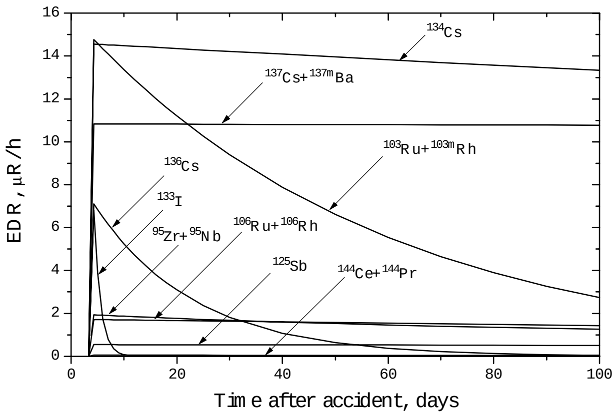


Fig. 1. Characteristic dependence of EDR at the height of 1 m from the ground surface for different radionuclides deposited in the Bryansk region (the ^{137}Cs contamination density is 37 kBq/m^2).

Table 1

Distribution of settlements of the Bryansk region by the number of collected samples in which ^{137}Cs activity is measured

Number of soil samples	Number of settlements	Part of total number settlements (3085), %
0-0[a]	855	27.7
1-1	291	9.4
2-10	1209	39.2
11-20	426	13.8
21-30	186	6.0
31-50	78	2.54
51-70	15	0.5
71-100	11	0.38
101-200	10	0.32
201-300	2	0.06
301-400	1	0.03
401-500	1	0.03

[This] line contains the number of settlements in which the ^{137}Cs soil contamination density has been reconstructed by interpolation.

Because of significant non-uniformity in depositions, especially in the zone of intense precipitation, for an acceptable estimate of ^{137}Cs soil contamination density (not worse than 30%) at least 10 soil samples should be measured. Data of Table 1 indicate that this condition is satisfied for approximately quarter of settlements. For the rest settlements the accuracy in estimation of average ^{137}Cs soil contamination density is not very high. This error is of significance for estimation of population doses in the settlements with high ^{137}Cs soil contamination density. So, for 43% of settlements in which less than 10 samples were collected (1,407 points) the ^{137}Cs soil contamination density estimated from γ-spectrometry of these samples is more than 37 kBq/m^2. The spread of the sample for these settlements is 4-2,800 kBq/m^2. For the settlements in which the ^{137}Cs soil contamination density was estimated with space interpolation this range is much smaller - 7-70 kBq/m^2.

The non-uniformity in depositions in the Bryansk region is illustrated by data of Figure 2. As can be seen from the Figure 2, the ratio of the maximum ^{137}Cs soil contamination density to the minimum is two orders of magnitude and is practically independent of the average value. For example, in the settlement Nizhnyaya Melnitsa of Medvedevsky soviet, Krasnogorsky district the minimum (9 kBq/m^2) and the maximum (1070 kBq/m^2) ^{137}Cs soil contamination densities differ by a factor of 120. The average ^{137}Cs contamination density in this settlement is 507 kBq/m^2. Therefore, in this settlement the average ^{137}Cs contamination density is lower the maximum by a factor of two, but higher the minimum by a factor of 53. In the settlement of Gudovka, Dushatinsky soviet, Surazhsky district the minimum (2.2 kBq/m^2) and maximum (245 kBq/m^2) densities of ^{137}Cs soil contamination differ by a factor of 110. The average ^{137}Cs contamination density in this village is 50 kBq/m^2. Thus, in this village the average ^{137}Cs contamination density is 5 times lower the maximum, but 20 times higher the minimum. Significant non-uniformity depositions were found in Klintsy. In this city the minimum (27 kBq/m^2) and maximum (1,760 kBq/m^2) ^{137}Cs soil contamination densities differ by a factor of 65 and the average contamination density is 390 kBq/m^2. In the most contaminated settlement of the Bryansk region the village of Zaborie, Zaborie soviet, Krasnogorsky district the minimum (840 kBq/m^2) and maximum (14,700 kBq/m^2) ^{137}Cs soil contamination densities differ by a factor of 17. The average ^{137}Cs soil contamination density in this village is 5,300 kBq/m^2.

For 10.8% (250 settlements out of 2,320) the minimum and maximum ^{137}Cs contamination densities differ by more than a factor of 10. These data suggest that in a significant number of settlements depositions were non-uniform across the territory. By way of illustration Figure 3 gives ^{137}Cs contamination map of the Bryansk region generated with the geoinformation system RECASS using the average contamination density of the settlement.

As of 1 January 1995 the overall average ^{137}Cs activity $\boldsymbol{Q}$ deposited in the territory of the Bryansk region can be estimated at 6.3 PBq (0.17 MCi), given the total contamination area $\boldsymbol{S}$ of $3.5 \cdot 10^4$ km^2. The value $\boldsymbol{Q/S}$ equal 180 kBq/m^2 is only 9.6 % higher the value 165 kBq/m^2 derived by averaging the ^{137}Cs contamination density by all soil samples. The minimum value $\boldsymbol{Q_{min}}$ estimated with RECASS is 3 PBq and the maximum $\boldsymbol{Q_{max}}$ - 12 PBq. The distribution of $\boldsymbol{Q}$ and $\boldsymbol{S}$ between different values of ^{137}Cs contamination density is shown in Table 2. Table 3 contains distribution of the number of settlements and number of residents of the Bryansk region by ^{137}Cs soil contamination density intervals.

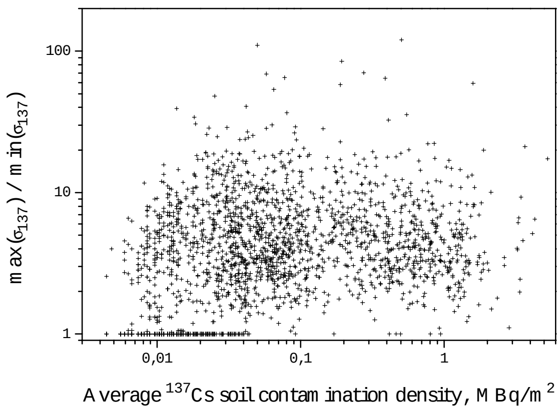


Fig. 2. Dependence of maximum measured ^{137}Cs contamination density maximum (σ_{137}) to the minimum (σ_{137}) on average ^{137}Cs soil contamination density.

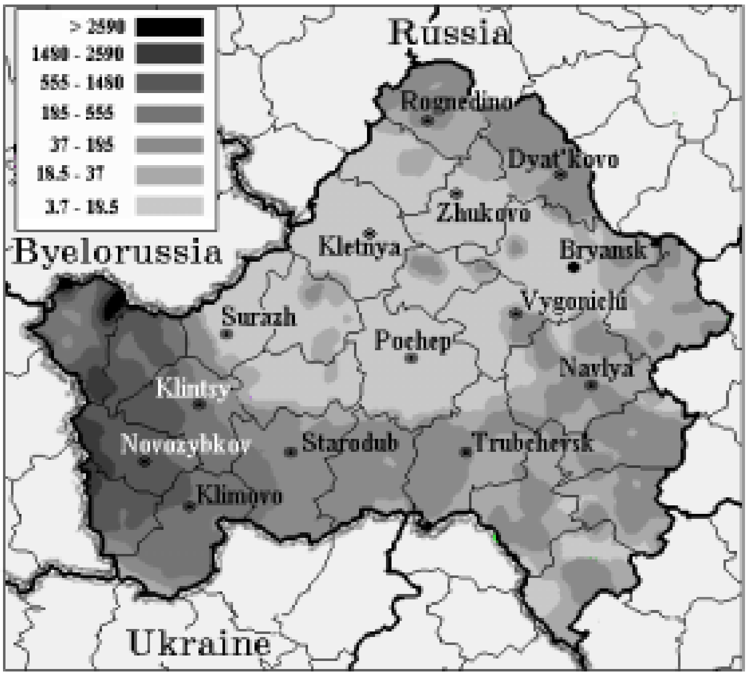


Fig. 3. Map of ^{137}Cs (kBq/m^2) contamination of the Bryansk region generated by the average contamination density.

Table 2

Distribution of minimum, average and maximum ^{137}Cs activity in soil *Q* and contamination areas *S* (With accuracy 9%) in the Bryansk region among different values of ^{137}Cs contamination density

σ_{137}, kBq/m^2	***Q***, PBq			***S***, 10^3 km^2		
	Min	Mean	Max	Min	Mean	Max
> 2,600	0	0.3	3.13	0	0.1	0.9
1,480-2,600	0.17	1.27	2.82	0.1	0.69	1.45
555-1,480	0.90	2.62	3.11	1.16	2.8	3.3
185-555	1.05	1.12	1.14	3.13	3.3	3.3
37-185	0.46	0.71	1.35	5.6	10.1	15.0
19-37	0.17	0.18	0.24	6.3	7.1	8.5
3.7-19	0.08	0.15	0.19	6.3	12.3	18.0

Table 3

Distribution of settlements of the Bryansk region by average ^{137}Cs soil contamination density

Contamination density range, kBq/m^2	Number of settlements	Part of the total number, %	Number of residents	Part of the total number of residents, %
3.7-19	1,193	38.6	782,700	53.2
19-37	573	18.6	152,500	10.3
37-74	456	14.8	194,200	13.2
74-100	149	4.83	46,100	3.13
100-185	140	4.54	47,200	3.21
185-300	120	3.89	29,300	1.98
300-555	164	5.32	119,800	8.14
555-1,000	158	5.12	71,250	4.84
1,000-1,480	85	2.76	21,260	1.44
1,480-2,590	32	1.04	5,900	0.4
2,590-3,700	12	0.39	1,540	0.1
3,700-7,400	3	0.10	830	0.06

Using the method described in [14] we generated «smooth» maps of average and maximum ^{131}I contamination density as of 20 May 1986 (the date when radioactive depositions were primarily finished) - Figure 4.

The average total activity of ^{131}I deposited in the territory of the Bryansk region is estimated at 8.9 PBq as of 20 May 1986 and the maximum - 31.9 PBq. These values correspond to 4.5% and 15.9% of the total ^{131}I release from the ChNPP referred to the time of the accident [14]. Due to the considerable variance in estimation of the radioiodine deposition density by ^{137}Cs deposition density we cannot state a lower bound of ^{131}I contamination density. It should also be noted that according to results of γ-spectrometry of soil samples [14] not more than 60% of the deposited ^{131}I in the territory of the region is statistically related to ^{137}Cs deposition. Therefore, the above estimates and deposition map are not ultimate and need to be refined using additional data. The range of reconstructed ^{131}I contamination densities in the settlements of the Bryansk region is very wide - from 0.1 to 10000 kBq/m^2 (as of 20 May 1986). Most of the settlements lie in the density interval from 10 to 1000 kBq/m^2.

Fig. 4. Map of ^{131}I (kBq/m^2) contamination of the Bryansk region generated by the reconstructed average density. The contamination density is referred to 20 May 1986.

Thyroid doses due to incorporated ^{131}I

In view of the selective accumulation of radioiodine in thyroid gland the thyroid system in residents of the most contaminated areas of the Bryansk region was subject to significant radiation effects. Because of a strong dependence of the thyroid weight on age (from about 2 g for 1 year old children to 20 g for adults) and due to the fact that, all other things being equal, the absorbed dose in the organ is inversely proportional to its mass, the thyroid in children was more exposed to irradiation.

The individual thyroid absorbed dose from iodine radionuclides is estimated with the best precision from measurements of individual dynamics of radioiodine activity and using an estimate of individual thyroid weight from ultrasonic studies. A mass-scale dosimetric survey of the population was conducted in the Bryansk region in May-June 1986 [8, 9]. The measurements of ^{131}I activity in thyroid among the Bryansk region residents were made using mobile dosimeters SRP-68-01 and a stationary unit for measuring radioiodine activity in thyroid used for therapeutic and diagnostic purposes in the clinical dosimetric laboratory of the Bryansk cancer dispensary.

For estimation and reconstruction of thyroid absorbed dose due to incorporated ^{131}I we used results of individual thyroid activity measurements for 1864 residents living at the time of measurement in 96 settlements of the 13 districts of the Bryansk region, among them 84 settlements, 9 towns and the cities of Bryansk, Novozybkov and Klintsy. Table 4 shows distribution of number of measurements by districts and types of settlements. The method for estimating the ^{131}I activity in thyroid is described at length in [13].

Table 4

Distribution of persons for whom thyroid measurements were performed in the Bryansk region

Administration district, city	Rural settlements		Town		City		Total	
	N_{sts} [a]	N_{mesh} [b]	N_{sts}	N_{mesh}	N_{sts}	N_{mesh}	N_{sts}	N_{mesh}
Bryansky	2	15	2	2			4	17
Vygonichsky	1	1					1	1
Gordeevsky	6	15	1	133			7	148
Zlynkovsky	14	88	2	182			16	270
Klimovsky	6	15	1	35			7	50
Klintsovsky	4	10					4	10
Krasnogorsky	25	272	1	116			26	388
Novozybkovsky	22	157					22	157
Pogarsky	1	4					1	4
Pochepsky			1	1			1	1
Starodubsky	2	3					2	3
Trubchevsky			1	3			1	3
Unechsky	1	4					1	4
Bryansk					1	29	1	29
Klintsy					1	18	1	18
Novozybkov					1	761	1	761
13 districts	84	584	9	472	3	808	96	1,864

[a] Number of settlements;
[b] Number of monitored persons.

For estimating the thyroid dose based on results of individual measurements we used the model proposed in [9] accounting for inhalation and ingestion pathways of ^{131}I intake. In doing this, the age-dependent parameters and biokinetic parameters, namely removal rate of radioactive iodine $\lambda_{th}(u)$ and thyroid weight $m_{th}(u)$ were taken from works [9, 17]. The normalization constant was determined for each person from the condition of equality of the modeled and measured ^{131}I activity at the time of measurement.

The spread of ^{131}I deposition densities in the points where the measured persons were living was 3.7 kBq/m^2 (as of 20 May 1986) in the village of Suponevo, Bryansk district in which 1 person was measured to 6.6 MBq/m^2 in the village of Zaborie, Krasnogorsk district with 25 persons measured.

The statistical analysis of the derived estimates of thyroid doses for 1864 measured persons shows that the dose distribution can be approximated by the log-normal law with the following parameters: the average geometric value of 84 mGy, the standard average geometric deviation of 3.9, the mathematical expectation of 278 mGy and the standard deviation of 716 mGy. Likewise, the distribution in the number of measured persons by radiation doses divided by reconstructed ^{131}I deposition density in the settlement as of 05/20/1986 also takes the form of log-normal law with the parameters: the average geometric value 0.081 mGy/(kBq/m^2), the standard average geometric deviation of 4.2, the mathematical expectation 0.41 mGy/(kBq/m^2) and the standard deviation 1.68 mGy/(kBq/m^2). The analysis of calculation results indicates that the spread of dose distributions is practically independent of ^{131}I deposition density.

Reconstruction of thyroid doses for the residents of the Bryansk region not subject to measurements

It can be shown that the integral Q_{th} of the activity absorbed by the thyroid and the internal dose D_{th} due to this intake are proportional. All other things being equal, the proportionality coefficient is dependent on age only. Therefore, in the spread pattern in the coordinates (Q_{th}, D_{th}) (the correlation coefficient estimated by 1864 measurements is 0.798) one can see data series as radial lines relating to different persons from different settlements, but of the same age. As data analysis shows, the lines with lower slope to the axis Q_{th} corresponds to groups of persons of older age. To eliminate the age dependence of the derived database we performed reduction of the radiation doses and thyroid activity integrals for all the measured persons to parameters of an adult using the relations:

$$D_i^* = D_i \cdot \frac{f_D(u^*)}{f_D(u_i)} \cdot \frac{M_{th}(u_i)}{M_{th}(u^*)} \cdot \frac{M_{milk}(u^*)}{M_{milk}(u_i)};$$

$$Q_i^* = Q_i \cdot \frac{q(t_i,u^*)}{q(t_i,u_i)} \cdot \frac{M_{milk}(u^*)}{M_{milk}(u_i)}; \qquad (1)$$

$$Q_i = C_i \cdot f_D(u).$$

Where $f_D(u) = \int_0^\infty q(\tau,u) \cdot d\tau$, u^* = 18 years of age; $M_{th}(u_i)$ is the thyroid weight in a person of age u_i; $M_{milk}(u_i)$ is daily consumption of milk for a person of age u_i; C_i is normalization constant.

This reduction procedure has significantly reduced the spread in dose distribution.

At the next reconstruction step we estimated parameters of distribution in reduced doses $\boldsymbol{D^*_i}$ for the residents of the settlements and then possible correlation between them and reconstructed ^{131}I deposition densities was sought. Consideration was given to those settlements in which the number of measured persons was more or equal 10. Altogether, we selected 21 settlements with 1,633 measurements of ^{131}I thyroid incorporated activity: 13 in villages (359 measurements); 5 towns (466 measurements) and 3 cities (Bryansk, Klintsy, Novozybkov - 808 measurements).

A typical form of the distribution for reduced doses estimated from individual thyroid measurements of persons living in the same settlement is illustrated in Figure 5 by data for Mirny, Gordeevsky district and Krasnaya Gora, Krasnogorsky district.

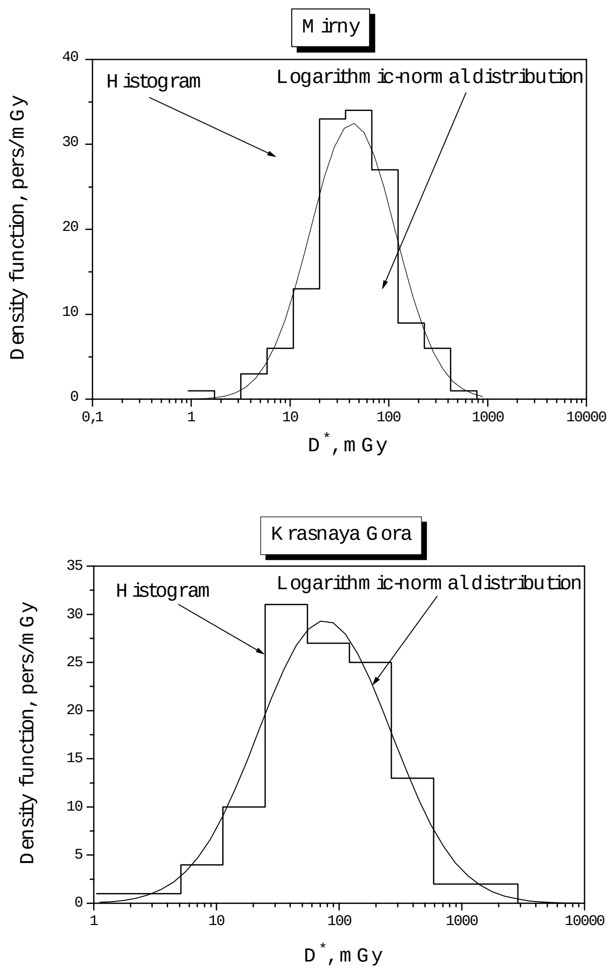


Fig. 5. Density function for the number of measured persons living in 1986 by thyroid dose reduced to the adult dose.

Then the data were handled as follows:

- for each settlement we estimated parameters of log-normal law for population distribution by reduced thyroid doses - mathematical expectation, standard deviation, median, average arithmetic value and average square error;
- all settlements were grouped by three categories:

- villages in which residents are assumed to consume milk only from private sector cows and the ^{131}I deposition density on pastures is the same as reconstructed density for the settlement itself;

- towns and cities for which it was assumed that the population consumes milk from public sector cattle of a given district and ^{131}I deposition density on pastures is identical to the density averaged over the whole district area;

- the city of Bryansk for which it was assumed that the residents consume milk from public cattle of the Bryansk district and adjacent 11 areas and the average ^{131}I deposition density on pastures where this milk was produced is identical to the density averaged over the area of all these districts.

For each of the above groups (index g) of settlements we draw a linear regression between the average reduced dose and average ^{131}I contamination density referred to 20 May 1986.

$$\overline{D}_g^* = K_g \cdot \overline{\sigma}_g^{131}. \qquad (2)$$

By way of example Figure 6 shows results of regression analysis for villages of the most contaminated Krasnogorsky district of Bryansk region. The derived regression conversion coefficients K_g are summarized in Table 5.

Using data of Table 5 and reconstructed average ^{131}I deposition densities for all settlements of the Bryansk region we first reconstructed average thyroid doses for adults. The average dose for a person of a given age was then derived by multiplying by the coefficient accounting for dependence of thyroid weight, ^{131}I biokinetics parameters and volume of milk consumption on age. The age dependence of this coefficient $\gamma(u)$ is given in Figure 7.

Table 5

Values of the regression coefficient K_g for the settlements of the Bryansk region

Administrative unit	K_g, mGy/(kBq/m^2)	Error K_g, mGy/(kBq/m^2)
Zlynkovsky district[a]	0.027	0.004
Krasnogorsky district[a]	0.054	0.021
Novozybkovsky district[a]	0.014	0.006
Average for the above districts[a]	0.049	0.007
Towns and cities[b]	0.045	0.02

[a] Rural settlements; [b] The data of measurements in Novozybkov are not used.

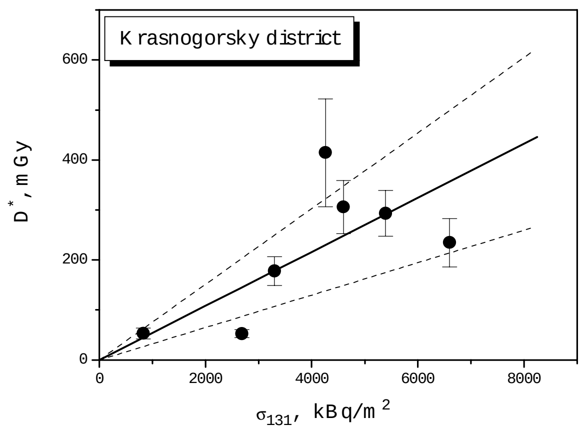


Fig. 6. Villages in Krasnogorsky area of the Bryansk region in which individual thyroid measurements were made (more than 9 persons). The statistical dependence between the average reduced thyroid dose and average ^{131}I soil contamination density in a settlement. The dotted lines are 95% confidence bounds of the regression line.

Fig. 7. Dependence of the ratio $\gamma(u)$ of the average thyroid dose to average thyroid dose on age for adults.

Collective thyroid doses for the population of the Bryansk region

For estimation of collective external and internal whole-body doses and internal thyroid exposure for residents of the Bryansk region we used the following data and assumptions:

- the number of residents in the settlements of the region by data of the 1989 census. Data on the population are not available for 140 of 3,085 points. The permissible inaccuracy in determination of the number of residents in the region as the total of residents n_k in separate points is not more than 0.1%.
- age distributions of residents in villages and towns were taken to be equal to those characteristic of the district according to the 1989 census (regional statistical reference book). These data were used for calculating the fractions of $P_{v,t}(u_i)$ of the i-th age in the villages and towns.
- for those villages and towns in which no thyroid measurements were made in May-June 1986 the average internal dose was estimated by dose coefficients K_g (Table 5) and average ^{131}I contamination density, for others (except Bryansk) dose estimates from individual thyroid measurements were used. For some settlements for which according to [10] protection measures have been implemented adjustments were made.
- because of a small number of measured persons in Bryansk and lack of data confirming that they consumed local milk we did not use the available thyroid measurement data for Bryansk. For adults of Bryansk we used the value K_g from the last line of Table 5 and ^{131}I soil contamination density (30 kBq/m^2 as of 20 May 1986) averaged over 11 areas adjacent to Bryansk. We compare the derived estimates for Bryansk. According to individual measurement data the average thyroid dose for adults is 27.3 mGy, which is higher than in Novozybkov - 13.6 mGy (without allowance for countermeasures). We also used the reconstructed value 0.045×30=1.3 mGy, which is 21 times lower the above dose. The calculated contribution of Bryansk to the collective thyroid dose corresponds to the contribution of 11 areas to the total reconstructed ^{131}I contamination density. Thus we use a very conservative estimate of thyroid dose for residents of Bryansk, as to date this problem has no conclusive solution.

Given the assumptions made it can be easily shown that the contribution of PD_k of the k-th settlement to the collective dose of the thyroid dose is:

$$PD_k = K_k \cdot \bar{\gamma}_k \cdot n_k \cdot \bar{\sigma}_k^{131}, \qquad (3)$$

where:

$$\bar{\gamma}_k = \sum_i p_k(u_i) \cdot \gamma(u_i). \qquad (4)$$

The age distribution of residents by districts of the region with the made assumption influences the coefficient γ_k within 30%. As a rule, because of a larger proportion of children it is higher for city dwellers than for rural population.

Results of estimation of collective thyroid dose due to incorporated ^{131}I for the residents of the Bryansk region are presented in Table 6 and Figure 8. As can be seen from Table 6 the largest contribution to the collective thyroid dose is made by Klintsovsky (35.3%), Krasnogorsky (22%) and Novozybkovsky (13.1%) districts of the Bryansk region.

Table 7 includes some generalized characteristics of the Bryansk region contamination and distribution of collective thyroid dose due to radioiodine across the territory with different ^{137}Cs contamination density.

So, we presented the results of estimation and reconstruction of thyroid doses from incorporated ^{131}I among residents of the Bryansk region in 1986. These results were used to study dose response of the thyroid cancer incidence rate among children and adolescents and to estimate radiation risks.

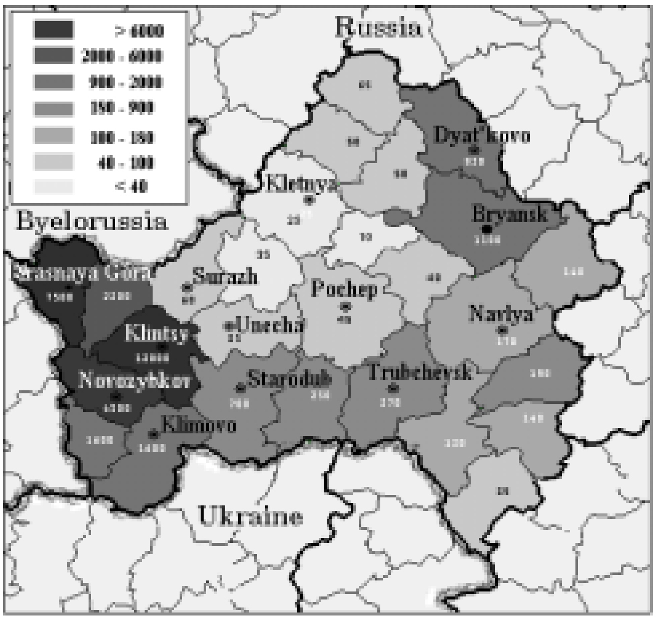


Fig. 8. Map of distribution of one collective thyroid dose due to incorporated ^{131}I as a result of the Chernobyl accident for residents of the Bryansk region. The numbers within the districts are collective doses in person·Gy and average thyroid dose (from Table 6) in mGy.

Table 6

Collective thyroid dose due to incorporated ^{131}I for residents of the Bryansk region of RF

District	Population[a], persons	Average[b] dose, mGy	Collective dose (PD), person Gy	Contribution to PD, %	Number of settlements
BRASOVSKY	27,220	7.0	191	0.56	86
BRYANSKY	537,650	2.1	1140	3.33	102
VYGONICHSKY	23,630	1.7	41.9	0.12	88
GORDEEVSKY	16,590	140	2,240	6.54	88
DUBROVSKY	21,270	2.3	47.9	0.14	123
DYATKOVSKY	83,520	11	940	2.75	51
ZHIRYATINSKY	8,740	1.5	12.8	0.04	74
ZHUKOVSKY	36,750	1.4	52.9	0.15	92
ZLYNKOVSKY	17,510	93	1,630	4.76	63
KARACHEVSKY	40,290	3.5	143	0.42	146
KLETNYANSKY	23,380	1.2	27.5	0.08	96
KLIMOVSKY	40,280	40	1,600	4.67	151
KLINTSOVSKY	108,250	110	12,100	35.4	146
KOMARICHSKY	21,750	6.5	142	0.42	101
KRASNOGORSKY	22,800	330	7,510	22.0	104
MGLINSKY	24,390	1.5	36.9	0.11	135
NAVLINSKY	31,970	5.3	170	0.50	90
NOVOZYBKOVSKY	62,840	71	4,490	13.1	116
POGARSKY	38,140	6.6	252	0.73	134
POCHEPSKY	48,980	1.0	47.0	0.14	254
ROGNEDINSKY	10,890	6.0	65.1	0.19	111
SEVSKY	21,200	4.0	85.2	0.25	87
STARODUBSKY	50,900	14	690	2.0	177
SUZEMSKY	27,480	4.6	127	0.37	57
SURAZHSKY	31,800	1.9	61.9	0.18	129
TRUBCHEVSKY	45,220	6.0	272	0.80	168
UNECHSKY	49,140	1.7	85.1	0.25	116
ALL DISTRICTS OF THE REGION	1,472,580	23	34,201	100	3,085

[a] By data of the 1989 census of the former USSR population;
[b] Ratio of collective dose to population.

Table 7

Collective thyroid dose due to incorporated ^{131}I for residents of the Bryansk region of RF living in the territory with different ^{137}Cs soil contamination density

Contamination density, kBq/m^2 (Ci/km^2)	Average[a] ^{137}Cs soil contamination density, kBq/m^2	Contamination area, km^2	Number of residents, persons (x 1,000)	Average dose[b], mGy	Collective dose (PD), personGy	Part of the total ^{137}Cs activity in soil[c], %	Number of settlements
3.7 - 37	19	18,500	934	2.2	2,040	6.0	1,757
37 - 185	70	9,500	288	9.8	2810	11.1	754
185 - 555	333	3,300	149	120	17900	17.4	284
555 – 1,480	925	2,800	93	85	7850	40.9	243
> 1,480	1,924	800	9	400	3570	24.6	47

[a] Ratio of average deposited ^{137}Cs activity to contamination density;
[b] Ratio of collective dose to population;
[c] Average amount of ^{137}Cs in soil in the Bryansk region at the time of the Chernobyl accident is estimated at 6.3 PBq (0.17 MCi).

Estimation of radiation risks of thyroid cancer

The demographic data on sex and age structure of the population in the period from 1986 to 1996 were obtained based on official statistical data, both regional and national. In the analysis we used age distributions for all 27 administrative districts and the region as a whole and data on the population of 3085 population points based on the 1989 census. The size of population groups included in the analysis is presented in Table 8.

When estimating the difference in incidence rates in the Bryansk region and in Russia as a whole, we used data of official medical statistics on age structure of thyroid cancer incidence.

In the period from 1991 to 1996 the Bryansk dispensary (a specialized medical establishment dealing with diagnosis, verification, registration and treatment of malignant neoplasms) has accumulated data for 68 cases of thyroid cancers among children and adolescents at exposure time (47 cases among girls and 21 cases among boys of 0-17 years at the time of the accident).

For deriving individual estimates of thyroid internal dose for children and adolescents we used the following procedure. In the previous sections of the article we reconstructed thyroid internal doses for adults and for each population point of the Bryansk region. The thyroid dose among those who have developed cancer was determined using the residence address at exposure time (the name of the population point) and dose dependence on age at exposure time (Figure 7). The mean absorbed dose for all those who have developed cancer was estimated at 0.11 Gy (for both sexes). For the population with undiagnosed cancers we calculated the distribution of collective dose by age for each population point. This estimation was made using the size of population in a particular population point, sex and age distribution of the population in the district to which the population point belongs and the age dependence of the thyroid internal dose. Then the cases were grouped by dose intervals. These were selected in such a manner that the number of persons with cancer in each interval was approximately the same. Results of this work are shown in Table 8. Distributions of cases, population size in each dose group and mean dose among persons without cancer in the dose groups are included in Table 1.

Table 8

Distribution of thyroid cancer cases among children and adolescents in the Bryansk region of RF for selected dose intervals

Males (age at exposure 0-17 years)				Females (age at exposure 0-17 years)			
Dose interval, mGy	Number of cases	Number of persons[a]	Mean dose, mGy[b]	Dose interval, mGy	Number of cases	Number of persons[a]	Mean dose, mGy[b]
0 - 2	4	45,962	1.2	0 - 2.5	11	52,328	1.3
2 - 7	5	59,285	3.9	2.5 - 11	13	65,161	5.2
7 - 270	6	75,956	48.6	11 - 150	11	50,849	42
270 - 950	5	8,521	442.8	150 - 3400	12	16,686	430
0 - 950	21	189,724	57.0	0 - 3400	47	185,024	56

[a] Number of persons of the age 0-17 years living in the Bryansk region at the accident time in the given dose interval of the population point;

[b] Absorbed internal thyroid dose averaged over the number indicated in the previous column.

For estimating the risk coefficients we used the method of maximum likelihood, by which cases are considered as independent Poisson random variables.

The logarithm of the likelihood function is:

$$LnL = \sum_k \left[n_k \times ln(\lambda_k) + \sum_i ln(t_{i,k}) - \lambda_k \times \left(\sum_i t_{i,k} + T_k \times (N_k - n_k) \right) \right] \quad (5)$$

where k is the number of dose intervals; T_k is time interval from the accident time to the end of 1996; $t_{i,k}$ is time interval from the accident time to detection of the i-th case in the k-th dose group; N_k is the number of residents in the k-th dose group; n_k is the number of cases in the k-th dose group; λ_k is the thyroid incidence rate in the k-th dose group.

The risk coefficients EAR and ERR were determined under the assumption of linear dependence of the thyroid cancer incidence rate on dose:

$\lambda_k = \lambda^s + EAR \times D_k$ - is the model of absolute risk, (6)

$\lambda_k = \lambda^s \times (1 + ERR \times D_k)$ - is the model of relative risk, (7)

where λ^s is the spontaneous incidence rate among the residents of the Bryansk region who were children and adolescents at exposure time (the value λ_k at zero dose); D_k is the mean thyroid internal dose in the k-th dose group.

Thus, the estimation parameters in models (6) and (7) are the values λ^s, EAR and ERR. They were estimated by finding the maximum of the likelihood function (5).

The confidence intervals for these parameters were determined based on asymptotic properties of the maximum likelihood estimates.

The work also compares the spontaneous thyroid cancer incidence λ^s estimated as parameter of models (6) and (7) with the expected incidence rate for the considered group estimated using the thyroid incidence rate in Russia. The estimate of the expected incidence rate for the considered period λ^{ex} is derived by the formula:

$$\lambda^{ex} = \frac{\sum_t \sum_u n_{u,t} \times \lambda^R_{u,t}}{\sum_t \sum_u n_{u,t}}, \quad (8)$$

where t is the calendar time, u is the attained age; $n_{u,t}$ is the age structure of the population under consideration; $\lambda^R_{u,t}$ is the thyroid incidence rate in Russia.

Results and discussion

The results of the processing data given in Table 8 are included in Figure 9. It can be seen from Figure 9 that the dose response of the incidence rate is close to linear, which is consistent with the data published in [1, 2], confirms the appropriateness of models (6) and (7) and, to a certain extent, demonstrates adequacy of the dose estimates.

Table 9 illustrates the values of the risk coefficients and spontaneous incidence rate with 95% confidence intervals. The derived results are indicative of the statistically significant increase in thyroid cancer incidence rate among children and adolescents at the accident time with the increase in thyroid internal dose and a significant excess of the thyroid incidence rate among the said contingent above the spontaneous level in the period under consideration.

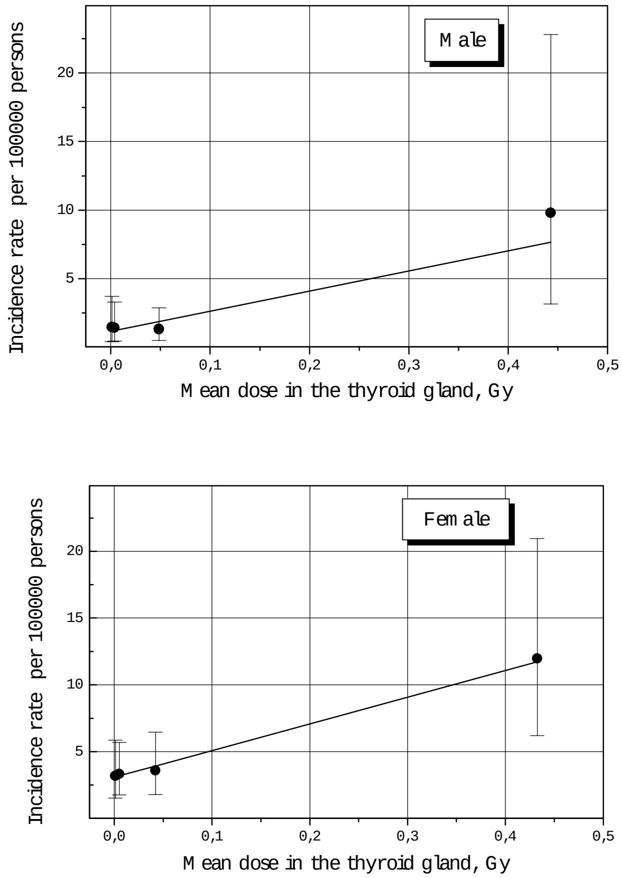


Fig. 9. The thyroid cancer incidence rate among children and adolescents of different sex at the accident time as a function of thyroid internal dose from incorporated ^{131}I (age at exposure 0-17 years).

Table 9

Estimates of radiation risks for 68 thyroid cancer cases among children and adolescents in the Bryansk region of RF (0-17 years at the accident time)

Parameter	Males	Females
Excess absolute risks $[10^4$ person years $Gy]^{-1}$ (95% CI)	1.5 (0.0, 2.8)	2.0 (0.5, 3.5)
Spontaneous thyroid incidence rate for 100000 persons (95% CI)	1.2 (0.5, 1.8)	3.1 (2.0, 4.2)
Excess relative risk $[Gy]^{-1}$ (95% CI)	12.7 (0.3, 24.5)	6.5 (1.6, 11.2)

The derived estimates of the excess absolute risk are lower the value 4.4 $[10^4$ person years Gy$]^{-1}$ presented in [2] by a factor of 2.5 or so. This may be because the cases considered in study [2] relate to external exposure of thyroid, whereas this study deals with internal exposure of thyroid to incorporated ^{131}I. According to [1] the radiation risk from external irradiation of thyroid may exceed the risk with internal exposure to incorporated iodine radionuclides by a factor of 2-5, though it is worth noting that this conclusion for this particular age group was drawn based on the study of a limited number of cases (about 10 cases).

The work also considers the influence of the number of dose intervals, within which the thyroid incidence cases were grouped, on the value of EAR. By changing the dose intervals from 3 to 9, provided the number of cases within the intervals was approximately the same, we had the value EAR changing in the range from 1.8 $[10^4$ person years Gy$]^{-1}$ (3 intervals) to 2.2 $[10^4$ person years Gy$]^{-1}$ (6 intervals).

The value of relative risk (7) is influenced by the spontaneous incidence rate. For girls in the considered interval of the attained age this coefficient appeared to be higher that for boys by a factor of 2.6.

Let us compare the incidence rate for the considered group with expected values derived with the assumption that the age dependence of the incidence rate in the Bryansk region is the same as for Russia as a whole. Table 10 presents incidence rates (for 10^5 persons) for the periods 1986-1990 and 1991-1996.

Table 10

Thyroid incidence rate per 100000 persons in the Bryansk region of RF in different observation periods

Sex	Females		Males	
Observation years	1986-1990	1991-1996	1986-1990	1991-1996
Observed	0.24	4.21	0.17	1.83
Expected	0.64	1.04	0.15	0.22
Spontaneous	1.9[a]	3.12	0.77[a]	1.23

[a] With correction for the screening effect and regional differences.

It may be concluded from Table 10 that the spontaneous thyroid cancer incidence rate in the period 1991-1996 in the Bryansk region is higher that for Russia as a whole for females by a factor of 3 (3.12/1.04) and for males by a factor 5.6 (1.23/0.22). The values of the spontaneous incidence rate in the period 1991-1996 are taken from Table 9. It may be speculated that the higher spontaneous incidence rate for Bryansk region in this period is due to regional differences in incidence and the screening effect. By multiplying the expected values of the incidence rate in the period 1986-1990 by these ratio, we get the estimate of spontaneous level in the period from 1986 to 1990 with allowance for the screening effect and regional differences for the considered group - 1.92 for females and 0.84 for males.

If we compare the derived values for spontaneous thyroid cancer incidence rate with the observed values in this period we will notice that the detectability of spontaneous cancers in the period 1986-1990 increased by a factor of 5-8 (the screening effect).

It would be worthwhile to answer the question: what proportion of all thyroid cancers in the period 1991-1996 are radiogenic cancers? In other words what is the value of the attributive risk? For estimating the number of radiogenic cancers we use the derived values of excess absolute risk EAR, the number of observation person-years and mean thyroid internal dose among those who developed thyroid cancer (0.11 Gy). The estimate indicates that among 68 cases 43 cases may be radiation induced, i.e. the attributive risk is 63%.

Conclusion

In the paper using the analysis of the radio ecological situation in the Bryansk region after the Chernobyl accident and data of individual thyroid radiometry carried out in May-June 1986 among a limited number of residents, we derived the estimate (most probably, a lower bound, as the value of collective dose of 0.54 million person for the residents of Bryansk cannot be considered as determined with required accuracy due to very scarce data of individual thyroid radiometry representative of a big city) of the collective thyroid internal dose from incorporated ^{131}I among the whole population of the region (1.47 million people) which equals 34.2 thousand person Gy (mean dose of thyroid internal irradiation is 23 mGy). The results of reconstruction of absorbed thyroid internal dose for all population points of the Bryansk region were used as the basis for the analysis of radiation risks and dose response of thyroid cancer incidence rate among children and adolescents at the time of the Chernobyl accident.

The results of the analysis can be summarized as follows:

- there is evidence of a statistically significant difference in the thyroid cancer incidence rate among children and adolescents at exposure time from the spontaneous level in the period 1991 to 1996;
- the estimates of the coefficients of risk of inducing radiogenic thyroid cancers for the studied group were the following:

the excess absolute risk EAR $[10^4$ person years Gy$]^{-1}$ - 1.5 (0.0-2.8, 95% CI) and 2.0 (0.5-3.5, 95% CI), respectively for males and females, and, accordingly, the excess relative risk ERR - 12.7 (0.3-24.5, 95% CI) and 6.5 (1.6-11.2 95% CI);

- detectability of spontaneous thyroid cancers among children and adolescents at exposure time in the period 1986-1990 increased by a factor 5-8 due to the screening effect;

- the attributive risk of the induction of radiogenic thyroid cancers in the period 1991-1996 is 63%. This means that at least every second detected thyroid cancer is radiation induced.

The revealed regularities in the growth of thyroid incidence rate among the people living at the time of the Chernobyl accident in the Bryansk region of RF will be later verified both for a larger number of cases detected in the Bryansk region and other contaminated areas of Russian Federation, in particular Kaluga, Oryol and Tula regions. At the same time, we will try to carry out a more accurate reconstruction of collective thyroid internal doses in these regions.

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