Thyroid doses for the population of Russia as a result of the Chernobyl accident (retrospective analysis)

Stepanenko V.F., Tsyb A.F., Gavrilin Yu.I.*, Khrushch V.T.*, Shinkarev S.M.*, Skvortsov V.G., Kondrashov A.E., Yas'kova E.K., Ivannikov A.I., Parshkov E.M., Shakhtarin V.V., Moskovko L.I., Petin D.V., Chebotareva I.V., Proshin A.D., Rozhko Yu.N.**, Dorokhov V.V.**, Rivkind N.B.**, Kvitko B.I.**, Kuz'min P.S.**, Leshakov S.Yu.***, Omel'chenko V.N.*****

Medical Radiological Research Centre of RAMS, Obninsk, Russia;
* Institute of Biophysics, Russia;
** Department of Health, Administration of Bryansk region;
*** Department of Health, Administration of Kaluga region.

The paper discusses a methodological approach developed for reconstruction of thyroid doses from internal exposure to ^{131}I and prospects of future work in this field. Estimated levels of thyroid irradiation for the population of Russia after the accident are presented. These results have been obtained based on the retrospective analysis using the developed approach. Also, long-term health consequences of thyroid irradiation in the population of Russia have been predicted. Retrospective estimates have been made for individual thyroid doses for children and adolescents with the diagnosis of thyroid cancer living on the contaminated areas.

Introduction

The recent data are indicative of an increase in the frequency of detection of malignant neoplasms of thyroid on the territories contaminated after the Chernobyl accident [1, 2]. This enhances the importance of the studies to comprehensively assess the factors of thyroid exposure to radiation. In this respect, based on available results of measurements of radioiodine in thyroid and various characteristics of the environment and using additional data which can be obtained in the near future, it is necessary to bring the accuracy of dosimetric evaluations of thyroid exposure to the level required by practical medicine and epidemiological studies, ideally, to the accuracy which would allow adjustment of dose coefficients of risk of thyroid diseases in irradiated persons. This problem should be first approached from the standpoint of total absorbed dose, namely internal radiation dose resulted from intake of radioactive isotope ^{131}I.

1. Key characteristics of available arrays of dosimetric data

In essence, three classes can be identified in individual internal doses of thyroid exposure to radioactive iodine:

Class 1 includes individual doses calculated from measurements of ^{131}I content in thyroid (people examined in May-June 1986). With all reservations concerning errors in measuring radioiodine in thyroid and uncertainties in calculation models used for estimation of individual doses, these data should be referred to as most reliable and objective.

Class 2 consists of estimates of individual doses for those population points for which sufficient amount of data of Class 1 are available. Based on results of Class 1, parameters of distributions of individual internal doses for corresponding age groups (mean value and deviation from it) are determined and then for a specific individual for whom data of Class 1 are not available, an individualised dose is estimated after additional information on life style, milk intake and other information is provided. While this additional information is missing, as a personal characteristic of thyroid internal irradiation mean values for a corresponding age group are taken. The objectivity of such characteristics is quite high, as they were derived on the basis of direct measurements of radioiodine in the thyroid.

Class 3 includes estimates of individual internal thyroid doses for residents of the rest populated points (which are the majority) for which the required amount of Class 1 data are not available and it is not possible to derive estimates of Class 2. In this case the group characteristics of internal exposure of thyroid can be estimated from data on characteristics of the radiation situation and its formation in each populated point of interest using one of the calculation models.

The problem is that the existing data on the radiation situation are rather limited and they are not sufficient for application of the known well-developed multi-parameter models. The most realistic way to solve the problem is to use a large volume of data of Class 1 available for the contaminated areas for developing a semiempirical model of extrapolation-interpolation type which would be rather general, but reflect the knowledge of the basic processes responsible for thyroid exposure and be based on available empirical material. At the same time, it would be desirable that such a model be quite simple, i.e. would require only available information on formation of thyroid doses or information that can be obtained by the existing methods.

The features of large-scale measurements of radioiodine in thyroid in May - early June 1986 on the contaminated areas of Belarus, Russia and Ukraine and main aspects of the following verification of measurements, models used and individual internal thyroid doses have been described in detail in national and international publications and discussed at scientific conferences [3-13]. In general, it can be said that separate subsets of Class 1 data formed by now by different investigation groups differ either by the method of obtaining primary data of radioiodine measurements in thyroid or by schemes for calculating individual internal thyroid doses.

In May-June 1986 in Belarus, Russia and Ukraine an unprecedented dosimetric survey was undertaken which produced results of direct measurements of the radioiodine content in the thyroid in more than 400 thousand people. The survey was performed by numerous groups of specialists of differing training, working in different conditions (from specialised establishments to field conditions in the contaminated areas) and having at their disposal different types of measurement equipment (from energy-selective specialised devices to γ-radiation dose rate detectors of DF-5 type). As a result, a variety of factors influenced the reliability of results of direct measurements. Some of these factors have been identified and corresponding adjustments have been made, as, for example, was the case with measurements in Belarus which were distorted because of the wrong measurement procedure used and conversion of measurement units without indication of the type of device used [6].

One of the issues which are still debatable is a possible distortion of results of determination of ^{131}I in thyroid due to “ glow” of detectors because of external radioactive contamination of body and clothes and as a result of intake of other radionuclides and, first of all, radioisotopes of cesium (^{134}Cs, ^{137}Cs). It should be emphasised that the contribution of γ-radiation of incorporated radiocesium in the detector readings (not γ-spectrometric), when measuring ^{131}I content in thyroid, changes depending on the date of measurement: from insignificant in early-middle May 1986 to predominant in middle June and later. The Class 1 data bank on residents of Kaluga region [3, 13] contains information of May 1986 only. The Class 1 data bank for the population of Belarus has only individual doses determined based on measurements made not later than 6 June 1986. The data on residents of Bryansk, Tula and Orel regions based on the difference in detectors readings with the measurement geometry of “ thyroid” and “ thigh surface” [8] can significantly underestimate the true values of individual internal thyroid doses for those for whom external radioactive contamination of thigh surface was not eliminated.

By far, factors influencing the reliability of the determination of ^{131}I content in thyroid can not all be quantified. That is why, at this stage we use an approach based on conventional classification of results of ^{131}I content measurements in thyroid into several certainty groups. Each of these groups are assigned a relative error by experts. The data on more than 200 thousand residents of Belarus were first divided into three groups of certainty of ^{131}I determinations in thyroid with allowance for conditions of measurements and devices used with relative errors of 50, 300 and 500% [6]. As a result of verification of available data and related work, the Class 1 data bank on residents of Belarus contains about 130 thousand individual doses, whose certainty groups, in terms of ^{131}I measurement in thyroid, can be characterized by relative errors: to 60%, within 60 to 200% and 200 to 400% respectively. Assuming that the indicated intervals correspond to 95% confidence probability with lognormal distribution, the introduced certainty groups can be characterized by the values of standard geometrical deviation of 1.3; 1.7 and 2.2 (1-st, 2-nd and 3-d certainty groups, respectively).

The main body of Class 1 measurement data for residents of Kaluga region (about 28 thousand [3, 13]), Bryansk, Tula and Orel regions of Russia (about 3.3 thousand [8]) can be referred to the 2-nd certainty group (standard geometric deviation of 1.3 - 1.7). It should be emphasised that given a fairly large amount of Class 1 data for residents of a populated point, the random component of the error in determination of mean values goes down to quite acceptable values.

The above characteristics account for only part of uncertainty in determination of individual internal thyroid dose form ^{131}I. The second component of this uncertainty is related to models translating measured ^{131}I into absorbed dose. At present, most Class 1 data on residents of contaminated areas, i.e. Belarus [6], Russia (Kaluga region) [3, 13] and Ukraine [7] have been brought to practically the same methodological base outlined in Guidelines [14] and in work [15].

At the first stage all estimates of absorbed doses have been derived from the assumption of a short-time passage of a radioactive cloud using a model of " per os" intake of ^{131}I with local milk, which is primarily characteristic of rural residents and a model of inhalation intake with consideration of documented protection measures (such as evacuation or relocation to relatively " clean" areas). The minor differences in the used values of calculation parameters (constants of thyroid cleaning from ^{131}I for separate age groups, cleaning of pasture grass and leaf vegetables) should be taken into account at the next stage. The assumption of a short one-time contamination of the environment was based on data on daily depositions of ^{131}I registered by Goskomhydromet network which, regrettably, is not as dense as one would need for dose reconstruction. The general scheme of applying adjustments for the long-term character of fallout is described in detail in Guidelines [14] and will be used in future as much in detail as kinetics of local depositions of ^{131}I is refined, which was promised, in particular, by the authors of work [16].

A model of ^{131}I intake that differs in principle has been used for calculation of individual internal thyroid dose for population of Bryansk, Tula and Orel regions [8] (a " stepwise" model). It was assumed that during the first 15 days after the first fallout the radioiodine intake by people had the same rate and later on the rate was decreasing in accordance with effective half-period of cleaning of pasture grass equal to 5 days. In calculations account was taken of protection measures resulting in bans on consumption of contaminated milk. With no protection measures taken, the deviation of results of calculation with the " stepwise" model from those with the Guidelines model [14] do not exceed 20%, given the measurements of ^{131}I were made later than 15-20 days after radioiodine started to enter the body. It should be said that in all the populated points of Bryansk region discussed in work [8] protection measures banning consumption of contaminated milk were introduced. In such cases the results of calculation with the " stepwise" model for younger age groups and postponed dates of measurement can exceed by a factor of 1.4-1.5 the values calculated by Guidelines [14] using the model of one-time contamination of pasture.

As was pointed out earlier, the Class 2 data are estimated based on results of calculation of individual internal thyroid doses included in Class 1 for populated points in which part of residents underwent dosimetric survey in May - early June 1986.

At the first stage mean absorbed thyroid doses are determined for different age groups and then with account taken of mean daily consumption of milk in these groups and individual mean daily consumption for a person of known age (as of April 1986) an individualised absorbed dose is found. Implementation of this scheme became possible because records (" passports") were drawn up for more than 1000 populated points located on the contaminated areas of Belarus [17] and Russia [13]. Using these passports one can estimate not only the value of the personalised dose but also its confidence interval. Also, deviations from typical life style in a specific populated point can be taken into account.

When the passports were designed some assumptions were made, the principal of which are:

1. It is assumed that the distribution of individual doses within an age group is described by a lognormal distribution function with parameters found for each populated point documented in the passport.

2. It is assumed that the components related to ^{131}I intake with milk and inhalable air are also characterised by lognormal distribution.

3. It is assumed that in the absence of protection measures the mean arithmetic value of the inhalation dose of internal thyroid exposure in adults of any populated point is 20 times lower the mean arithmetic dose due to ^{131}I intake with milk (and leaf vegetables), and the standard geometric deviation of inhalation component of individual dose in all cases is 2.9. Such a large standard geometric deviation was taken with " a margin" to allow for possible variations in inhalation regime (from sleeping to active physical work) and local changes in ^{131}I concentration in the air.

4. It is assumed that the " per os" component of dose is wholly determined by ^{131}I intake with milk, and for a specific person ($\boldsymbol{k}$) from age group ($\boldsymbol{i}$) the " per os" component of individual dose $\boldsymbol{P_{ik}}$ is related to the component $\boldsymbol{P_{ic}}$ which is a mean for an age group ($\boldsymbol{i}$) in a given populated point with a simple relation:

$$\frac{P_{ik}}{V_{ik}} = \frac{P_{ic}}{V_{ic}}, \qquad (1)$$

where $\boldsymbol{V_{ik}}$ and $\boldsymbol{V_{ic}}$ is daily milk consumption by an individual ($\boldsymbol{k}$) and by individuals from the $\boldsymbol{i}$-th age group on the average in the populated point, respectively, L/day.

The results of polling regarding daily milk consumption among rural population in Belarus and Russia were similar to these, which leads us to assume that within an age group individual daily milk consumption is adequately described by a lognormal distribution with medians $\boldsymbol{V_{im}}$ and with practically the same standard geometric deviation of 1.6±0.1 [17, 18]. The values $\boldsymbol{V_{im}}$ accepted for rural population during passportization of the populated points of Belarus and Kaluga region of Russia are presented in Table 1.

In order to make the passports on internal thyroid exposure easier to use in practice, all initial data were divided into 19 age groups without regard for sex. Of them, the first 18 (children and adolescents) were formed with the step of 1 year (the first group - birth dates from 25.04.86 to 26.04.85) and the last 19-th group included all persons at the age of 18 years and older (as of 26.04.86).

Table 1

Median values V_{im} (L/day) of mean daily milk consumption by rural population of Gomel and Mogilev regions of Belarus and Kaluga region of Russia, accepted for passportization of populated points with respect to internal thyroid exposure

Region	Age on 1 May 1986, years			
	< 3	3 - 13	13 - 16	≥ 16
Gomel and Mogilev re-	0.4	0.4	0.5	0.7

gions of Belarus				
Kaluga region of Russia	0.5	0.4	0.4	0.7

The passport of a populated point on internal exposure of thyroid is a table of 19 lines (age) and 13 main columns (daily milk consumption from 0 to 4 L/day and a column for the case when personal information on daily milk consumption is not available). Each box of the table gives an absolute median estimate of internal thyroid dose from ^{131}I for which a standard geometrical deviation is given, which permits calculating bounds of confidence probability for an individualised dose value. The instruction on the passport use describes the procedure of determination of individualised dose including methods to correct the tabulated value, if personal conditions of thyroid dose formation differ from the typical ones (for example, arrival-departure dates, consumption of goat milk etc.). A scheme is described for calculating internal thyroid doses in infants due to intake of radioiodine with mother's milk and calculating doses received in the intrauterine period.

All aspects of drawing up the passports of populated points on internal thyroid exposure have been described in detail in [17-19, 21, 23].

Table 2 contains general information on Class 1 data banks and shows to what degree the populated points were covered by passports permitting an individualised estimate of internal thyroid dose (Class 2 data) to be derived for the population of the contaminated areas of Belarus and Russia

Table 2

Information on Class 1 data banks and number of populated points with passports in the contaminated areas of Belarus and Russia (Class 2 data) characterizing internal thyroid doses

Territories	Class 1 data: number of persons with individual doses calculated from measurements of ^{131}I content in thyroid, thousand			Class 2 data: number of rural populated points with passports
	Younger 18 years (on 26.04.86)	Adults	Total	
8 areas of Gomel region of Belarus [6]	25.4	63.1	88.5	678
5 areas of Mogilev region of Belarus [6]	4.5	8.9	13.4	253
Minsk [6]	7.3	12.9	20.2	-
Gomel, Mogilev, Mozyr and other contaminated areas [6]	3.3	5.2	8.5	-
7 areas of Kaluga region of Russia [3, 13]	24.2	3.7	27.9	140
Bryansk, Orel, Tula regions of Russia [8]	1.0	2.2	3.2	22*

* - Mostly populated points of town type.

2. Relation between internal thyroid dose in residents of a populated point and fallout density

The performed surveys of the areas contaminated after the Chernobyl accident have resulted in accumulation of a large volume of information enabling an in-depth analysis of relations between internal thyroid doses and characteristics of radioactive contamination in certain populated points. In order to avoid any major distortions in expected trends, the requirements were set for the data to be used for analysis.

Of more than 1000 populated points having passports on internal thyroid exposure, consideration was given only to those for which at least 25 individual dose estimates were available. It is clear that relations like " dose - area contamination level" can be analysed if data are comparable in terms of protection measures. Adjustments for such measures for specific populated points are strongly dependent on adopted calculation models. For example, in the case when the consumption of contaminated milk was banned 8 days after one-time contamination of pastures, the adjustment for multiplicity of reduction in internal thyroid dose calculated by the " stepwise" model [8] is by a factor of 1.9 higher that calculated by the Guidelines [14].

To avoid possible distortions related to such adjustments, we have excluded from the analysis all populated points from which residents had been evacuated prior to 5 May 1986 (Gomel region in Belarus).

Cities and district centres have also been excluded from the analysis as they were supplied with food stuffs in a different way as compared to rural populated points. The number of populated points meeting the above requirements was 250 in Gomel and Mogilev regions in Belarus and about 60 in Kaluga region, i.e. 1/3 of the total number of passportized points.

As basic data characterizing the contamination of populated points we used official data on surface density of ^{137}Cs depositions [24, 25]. We also relied on data of Institute of Nuclear Power, Minsk [26] and data obtained by specialists of Institute of Biophysics, Moscow (F.Levochkin, A.Titov, S.Panchenko et al) in determination of mean ratios $\boldsymbol{R_j}$ of ^{131}I content to ^{137}Cs (σ_{137}) in soil calculated by the time moment of main radioactive contamination of the $\boldsymbol{j}$-th populated point. The ^{131}I deposition density σ_{131}^{j} used in the correlation analysis was found from the relation:

$$\sigma_{131}^{j} = \sigma_{137}^{j} \cdot \boldsymbol{R}_j . \qquad (2)$$

The distribution of individual thyroid doses within relatively small territories, which the administrative areas are, is fairly well approximated by the lognormal function [18]. This can not be applied, however, to density of radioactive fallout and therefore, it would be unwise to include in the analysis procedure the properties which are specific for the lognormal function. Ultimately, it was decided that at the first stage of iteration a more objective quantitative characteristic of contamination of area $\boldsymbol{X}$ is a mean arithmetic value (hereinafter unless otherwise defined, we use the term " mean") of contamination density:

$$\sigma_{137}^{x} = \frac{1}{N} \cdot \sum_{j=1}^{N} \sigma_{137}^{j,x} , \qquad (3)$$

where $\sigma_{137}^{j,x}$ is mean density of contamination of the $\boldsymbol{j}$-th populated point located on area $\boldsymbol{X}$.

Then, of course, other values involved in the correlation analysis should be estimated by mean values. To avoid additional difficulties related to age features we used in the analysis mean values $\boldsymbol{D}_{j,x}$ of internal thyroid doses for adults of the $\boldsymbol{j}$-th populated point located on the area $\boldsymbol{X}$. As separate areas $\boldsymbol{X}$ we took administrative districts, which is, of course, not an optimum solution in terms of physics of transport of radioactive materials, but can be justified, as the first approximation, by lack of adequate description of these processes for all areas of interest.

Fulfilment of the above requirements, as applied to specific populated points, has also a negative side, as the group of populated points left for the analysis may appear not to be a representative sample for a corresponding area. Table 3 includes mean absorbed thyroid doses for three districts of Gomel region of Belarus located beyond the 30 km zone, for which the greatest amount of individual doses (Class 1) are available and a lot of populated points left after " sorting out" based on the above requirements. It should be emphasised that in these three areas the proportion of persons supported with Class 1 data is particularly high (more than half of all rural population).

As can be seen from data of Table 3 for the three areas of interest the samples of the populated points can be considered quite representative, at least with respect to the main indicator - mean dose.

The representativeness of samples of populated points for other areas of Belarus and Russia is rather difficult to be assessed in a similar way, since there is no guarantee that the body of Class 1 data for adults of these areas are representative.

The representativeness of samples of populated points left for correlation analysis $D_{j,x} \Leftrightarrow \sigma^{j,x}_{137}$, by the second characteristic - ^{137}Cs contamination density can be assessed by comparing the set σ^{x}_{137} found from the totality of official data with the mean values of $\sigma^{n,x}_{137}$ found with the sample from n_x of populated points left for analysis. These parameters for 11 administrative districts of Belarus and 3 areas of Kaluga region of Russia are given in Table 4. This table also includes mean values of ratios R_x of ^{131}I activity to ^{137}Cs activity referred to the date of principal contamination of area X, and a number m_x of populated points for which the values of R_x have been found based on direct measurements of samples. The columns of R_x and $\sigma^{n,x}_{137}$ also indicate mean square deviations of $R_{j,x}$ and $\sigma^{j,x}_{137}$ for separate populated points.

Table 3

Mean internal thyroid doses for adults of administrative districts of Gomel region of Belarus (territory beyond the 30-km zone) calculated from the whole array of data and from samples of populated points selected for correlation analysis

Parameter	Administrative district		
	Bragin	Narovlya	Khoiniki
Number of adults with individual doses	15084	2499	10560
Mean dose based on the whole data array, mGy	400	360	480
Number of populated points in a sample for a correlation analysis	70	21	47
Mean dose for a sample of populated points, mGy	320	390	450

Table 4

Main indicators of the radioactive contamination of areas and populated points selected for analysis of correlations such as $D_{j,x} \Leftrightarrow \sigma^{j,x}_{137}$; $D_{j,x} \Leftrightarrow \sigma^{j,x}_{131}$

R_x is the relation of ^{131}I and ^{137}Cs deposition densities referred to the date of main radioactive contamination of area X;
m_x is the number of populated points for which R_x is estimated.

Area	σ^{x}_{137}, kBq/m^2	R_x	m_x	$\sigma^{n,x}_{137}$, kBq/m^2	n_x
Districts of Gomel region, Belarus					
Bragin (outside 30-km zone)	330	29 ± 21	76	190 ± 170	70
Vetkov	440	13.7 ± 7.4	35	580 ± 330	11
Loev	92	23 ± 14	9	78 ± 92	19
Narovlya (outside 30-km zone)	470	16.9 ± 8.6	56	470 ± 230	21
Rechitsy	100	36 ± 35	11	85 ± 37	17
Khoiniki (outside 30-km zone)	480	24 ± 15	56	350 ± 240	47
Districts of Mogilev region, Belarus					

Klimovichi	52	22 ± 33	12	450 ± 300	7
Kostyukovichi	250	10 ± 15	26	1000 ± 440	19
Krasnopol	260	8.8 ± 2.9	69	1000 ± 920	18
Slavgorod	390	11.3 ± 7.2	34	580 ± 360	9
Cherikov	240	10 ± 12	16	670 ± 520	11
Districts of Kaluga region, Russia					
Zhizdra	110	–	–	96 ± 52	17
Ulyanovo	170	–	–	170 ± 70	20
Khvastovichi	89	–	–	150 ± 100	24

It can be seen from Table 4 that unlike Gomel and Kaluga regions, the samples for the areas of Mogilev region contain primarily the most contaminated (as compared to the mean) populated points located in the " patches" of radioactive depositions.

Table 5 for all considered administrative districts of Belarus and Russia contains empirical values of correlation coefficients $\boldsymbol{r}$ and the absolute values of correlation coefficients $\boldsymbol{r}_{0.1}$ and $\boldsymbol{r}_{0.01}$. If the latter are exceeded, with the given size of the sample, it means that there is a correlation between the considered values at a relatively low level of significance 0.1 and high level of significance 0.01, respectively, under the assumption of the normal distribution law of these random values.

Based on the data presented in Table 5 it can be stated that by a rather hard statistical test there is a positive correlation between $\boldsymbol{D}_{j,x}$ and $\sigma_{137}^{j,x}$ for all three areas of Kaluga region of Russia, populated points of Kostyukovichi and Krasnopol areas of Mogilev region and Bragin and Rechitsy areas of Gomel region of Belarus. As to populated points of other areas of Belarus indicated in Table 5, it is either lack of correlation or at best, a weak positive correlation (Vetkovsky and Klimovichesky areas). The positive correlation between dose $\boldsymbol{D}_{j,x}$ and contamination density $\sigma_{137}^{j,x}$ suggests that it is possible, in essence, to use the useful information incorporated in a specific value $\sigma_{137}^{j,x}$ to propose a way to determine values $\boldsymbol{D}_{j,x}$ for a specific populated point.

Table 5

Empirical values *r* of correlation coefficients of mean arithmetic dose of internal thyroid exposure in adults $D_{j,x}$ and ^{137}Cs contamination density $q_{j,x}(Cs)$ of populated point (*j*) on area *X* and bound values *r*(0.1) and *r*(0.01) which, if exceeded by absolute values r_x, indicate correlation of the values at significance levels 0.1 and 0.01, respectively.

Area	$\boldsymbol{r}$	$\boldsymbol{r}_{0.1}$	$\boldsymbol{r}_{0.01}$
Districts of Gomel region, Belarus			
Bragin	+ 0.48	0.20	0.30
Vetkov	+ 0.66	0.52	0.73
Loev	+ 0.33	0.39	0.58
Narovlya	+ 0.26	0.37	0.54
Rechitsy	+ 0.63	0.41	0.61
Khoiniki	+ 0.25	0.24	0.37
Districts of Mogilev region, Belarus			
Klimovichi	+ 0.84	0.67	0.87

Kostyukovichi	+ 0.68	0.39	0.58
Krasnopol	+ 0.68	0.40	0.59
Slavgorod	– 0.28	0.58	0.80
Cherikov	– 0.43	0.52	0.73
Districts of Kaluga region, Russia			
Zhizdra	+ 0.62	0.41	0.61
Ulyanovo	+ 0.64	0.38	0.56
Khvastovichi	+ 0.57	0.34	0.52

* - marked are the lines showing the areas for which $r > r_{0.01}$.

The methodological guidelines [27] in force recommend that the mean internal thyroid dose $D_{j,x}$ be estimated with:

$$D_{j,x} = K_x \cdot \sigma_{137}^{j,x}, \quad (4)$$

where K_x is " dose" proportionality coefficient whose value should be specified for each specific area.

Work [28] proposes a linear formula for any regions. In our designations it can be written as

$$D_{j,x} = 0.51 + 0.14 \cdot \sigma_{137}^{j,x}, \text{ mSv}, \quad (5)$$

where $\sigma_{137}^{j,x}$ is measured in kBq/m^2.

The data on populated points of the considered contaminated areas of Belarus and Russia show inadequacy of models (4) and (5). This is particularly well seen in consideration of values of the ratio $D_{j,x}/\sigma_{137}^{j,x}$ as a function of $\sigma_{137}^{j,x}$: at small values this ratio is much higher than at large ones [12]. Such a dependence is universal and is rather far from that described by relation (4). The calculation with model (5) does not give a good agreement with empirically found values either.

Table 6 includes characteristics of correlation relations between internal thyroid doses and measurements of ^{131}I soil contamination density available for some areas. The performed analysis has permitted presenting all data in the following equivalent forms:

$$D_{j,x} = 0.036 \cdot \sigma_{131}^{x} + 0.013 \cdot \sigma_{131}^{j,x} = \\ = 0.036 \cdot R_x \cdot \sigma_{131}^{x} + 0.013 \cdot R_{j,x} \cdot \sigma_{131}^{j,x}, \quad (6)$$

mGy,

where σ_{131}^{x}, σ_{137}^{x} are mean ^{131}I and ^{137}Cs contamination densities for populated points on areas X, respectively, kBq/m^2;

$\sigma_{131}^{j,x}$, $\sigma_{137}^{j,x}$ are mean contamination densities of the j-th populated point with ^{131}I and ^{137}Cs located on area X respectively, kBq/m^2;

R_x, $R_{j,x}$ are coefficients of correlation between ^{131}I and ^{137}Cs contamination densities.

Formula (6) can be rewritten as

$$D_{j,x} = 0.036 \cdot \sigma_{131}^{x}\left(1 + 0.4\frac{\sigma_{131}^{j,x}}{\sigma_{131}^{x}}\right) = \\ = 0.036 \cdot R_x \cdot \sigma_{137}^{x}\left(1 + 0.4\frac{R_{j,x}}{R_x} \cdot \frac{\sigma_{137}^{j,x}}{\sigma_{137}^{x}}\right). \quad (7)$$

It is clear that the second summand in the brackets will strongly influence the calculated value of dose $D_{j,x}$ only for those populated points for which mean contamination density of ^{131}I - $\sigma_{131}^{j,x}$ considerably exceeds the mean σ_{131}^{x} for the area. Meanwhile, on a whole, it can be said that in the zero approximation the internal thyroid dose in the population of specific populated points is primarily determined by the mean characteristic of radioactive contamination of the considered areas, and this can be explained by fundamental properties of the processes responsible for formation of internal doses.

Table 6

Statistical characteristics of the relation of mean internal thyroid dose $D_{j,x}$ and mean contamination density in populated points and areas ^{31}I - $\sigma_{131}^{j,x}$ and ^{137}Cs - $\sigma_{137}^{j,x}$

n is number of populated points (sample size);
$\sigma_{137}^{j,x}$ is a mean over the sample contamination density of the area;
r(^{131}I-^{137}Cs) is the correlation coefficient between $\sigma_{131}^{j,x}$ and $\sigma_{137}^{j,x}$;
$r(D_{j,x}$-^{131}I) is the correlation coefficient between $D_{j,x}$ and $\sigma_{131}^{j,x}$;
$r(D_{j,x}$-^{137}Cs) is the correlation coefficient between $D_{j,x}$ and $\sigma_{137}^{j,x}$;
$A_{j,x}$ is a free term of the equation of linear regression between $D_{j,x}$ and $\sigma_{131}^{j,x}$;
$B_{j,x}$ is the linear regression coefficient.

Estimated parameter	Administrative districts					
	Bragin	Khoiniki	Narovlya	Kostyukovi-chi	Krasnopol	K+K
n	42	26	13	11	8	19
$R_x \cdot \sigma_{131}^{j,x}$, MBq/m^2	9.6	11	8.1	2.5	2.3	2.4
$\sigma_{137}^{j,x}$, MBq/m^2	6.5 ± 0.78	9.1 ± 1.7	11 ± 2.3	7.4 ± 1.0	8.9 ±2.5	8.0 ± 1.2
r(^{131}I-^{137}Cs)	0.74	0.73	0.59	0.80	0.98	0.94
$r(D_{j,x}$-^{131}I)	0.30	0.46	0.17	0.75	0.82	0.80
$r(D_{j,x}$-^{137}Cs)	0.38	0.44	0.006	0.60	0.79	0.72
$A_{j,x}$, mGy	340	400	390	130	120	130
$B_{j,x}$, mGy/(MBq /m^2)	12 ± 59	10 ± 4.3	0.2 ± 4.9	12 ± 4	10 ± 3.2	10 ± 2.2

- \- K+K is combined data on Krasnopol and Kostyukovichi districts.

3. Justification of empirical relations with features of phenomena and processes responsible for formation of internal irradiation

The fact that fundamental natural processes are underlying the empirical relations (6), (7) can be illustrated by the characteristics of “dry” and “wet” depositions of radionuclides. For this purpose one can consider a hypothetical territory with the number of populated points sufficient for consideration of statistical regularities. On the other hand, let us suppose that this area is relatively small in size, and hence it can be realistically assumed that the integral of surface ^{131}I concentration in each populated point resulted from the passing radioactive cloud is practically the same.

It is obvious that the inhalation intake of radioiodine averaged for each age group should be almost identical in all populated points of the considered area. The main component of the internal thyroid exposure in rural populated points is due to radioiodine intake with milk, i.e. is directly related to contamination of pasture grass and to some extent, of soil which gets into the grazing cows. The proportion of radioiodine deposited on the grass surface depends on properties of grass itself and on chemical properties of compounds in which iodine was incorporated in the radioactive cloud. This may lead to a certain spread in the mean intake of radioiodine in different populated points of the considered area. It should be pointed out that the Chernobyl accident occurred at the beginning of grazing season when the density of grass mass per unit pasture area was far from equilibrium values and the total density of “dry” radioactive depositions did not differ significantly from soil contamination density. The value of deposition density grew sharply in case of local rainfall and other local processes referred to as “wet” depositions (fogs, hew). As a result, the contamination level could increase by dozens of times, while the amount of radioiodine on the grass could remain virtually the same as with dry depositions [29]. It is clear that the absorbed dose ***D*** of internal thyroid exposure in the same populated point could be almost the same as in another one, in which there was no rain and the ratio D/σ_{131} (where σ_{131} is density of soil contamination with iodine) differed for such a point by dozens of times too.

Figure 1 shows the ratio D/σ_{131} as a function of deposition density σ_{131} calculated in accordance with the model ECOSIS-87 [30] (curve 1) under the assumption of "dry" and "wet" depositions, with the same ^{131}I concentrations integral in the surface air layer. In addition to this model, a term was introduced related to cow's intake of the radionuclide with soil [20] (it is assumed that the cow eats 30 kg/day of fresh pasture grass, taking in 1 kg/day of soil). Also, a variant of the coefficient of radioiodine intake with grass, corresponding to the conditions of CIS countries [31] (curve 2) has been introduced. With the increase in σ_{131} the ratio D/σ_{131} is decreasing and tends to limiting values which (in a wide spectrum of adopted characteristics of pasture grass) lie in the range

$$(1.1 - 1.8)\cdot 10^{-8}\ \text{Gy}\cdot\text{m}^2/\text{Bq} =$$
$$= 0.011 - 0.018\ \text{mGy}\cdot\text{m}^2/\text{kBk}.$$

As can be seen this range includes the value 0.0135 $\text{mGy}\cdot\text{m}^2$/kBq accepted in formula (6) after generalising empirical data.

4. About applicability of developed semiempirical model to the conditions of the areas contaminated after the Chernobyl accident

The considerations presented in the previous section make us even more to believe that we have chosen the right approach to creating a simple workable model for reconstruction of internal thyroid doses in rural population of those contaminated areas for which results of direct measurements of radioiodine content in thyroid are not available. There is good reason to refer the model presented by formula (6) and its equivalent (7) to semiempirical, believing that it can be applied to all contaminated areas in Russia and Belarus. In essence, the question needs to be answered: does the semiempirical model provide more accurate estimates of thyroid doses in the populated points of the contaminated areas, on the average, as compared with (4) and (5)?

The performance of the above three models is convenient to be compared with dimensionless quantities - ratios of empirical values of dose $D_{j,x}$ found based on thyroid radiometry and values of $D_{j,x}$ calculated with formulae (4), (5) and (7), (8).

For practical calculations by formulae (7, 8) an important simplifying assumption has to be made: with the required data missing it is assumed that for each ***j***-th populated point considered as part of the area ***X***, the ratio $R_{j,x}$ is equal and equals a mean R_x assigned to area *X*. Then formula (7) is reduced to

$$D_{j,x} = 0.036 \cdot R_x \cdot \sigma_{137}^{x} \cdot \left(1 + 0.4\,\frac{\sigma_{137}^{j,x}}{\sigma_{137}^{x}}\right). \quad (8)$$

The values of the proportionality coefficient K_x (formula (4)) for each area ***X***, given sufficient amount of data ($D_{j,x}$, $\sigma_{137}^{j,x}$) can be determined by the least square method by the formula:

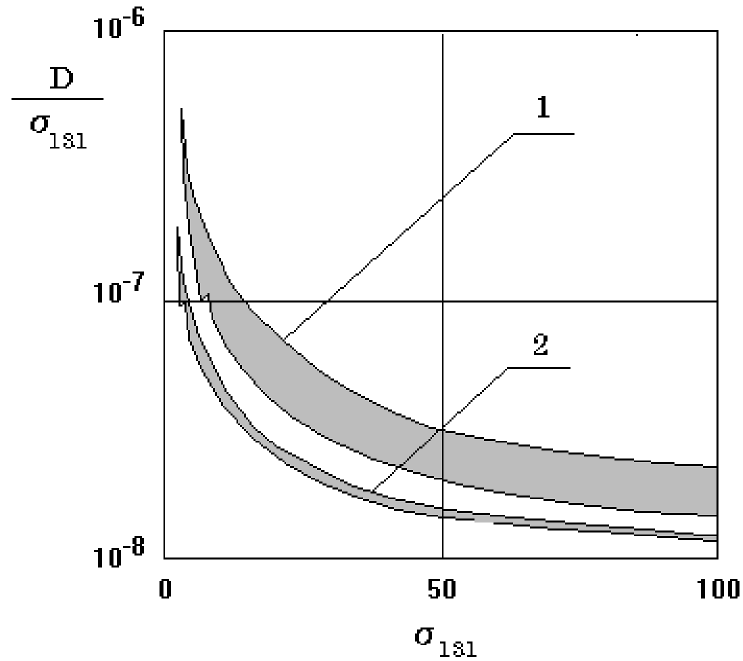

Fig. 1. Dependence of D/σ_{131} (ordinate axis), Gy·m²/Bq on ^{131}I deposition density - σ_{131} (abscissa axis, relative units) built based on calculation by ECOSIS-87 model [30] for "dry" and "wet" depositions.
1 - calculation by ECOSIS-87 model without modifications;
2 - calculation by ECOSIS-87 model with allowance for the coefficient of radioiodine grass intake corresponding to CIS conditions.

$$K_x = \frac{\sum_j D_{j,x} \cdot \sigma_{137}^{j,x}}{\sum_j (\sigma_{137}^{j,x})^2}. \qquad (9)$$

Yet, this approach does not work for those areas X for which values of $D_{j,x}$ are not available and for which the model is actually designed. In this case, there is the only solution: to take a certain area X_0 as a reference one and after determination of the proportionality coefficient K_{x0} for it from formula (9) it derive the value of the coefficient K_x from the relation:

$$K_x = K_{x0} \cdot \frac{R_x}{R_{x0}}. \qquad (10)$$

As a reference area we took Kostyukovichi district of Mogilev region in Belarus, for which the proportionality coefficient K_{x0} calculated by formula (9) appeared to be 0.21 mGy·m²/kBq.

The results of comparison of calculations by different models with empirical values, i.e. doses estimated from thyroid radiometry data are shown in Table 7. The data of this table account for the spread in ratios of empirical values to doses calculated by different model s- formulae (4), (5), (7) or (8).

It should be noted that in calculation by formulae (7) or (8) for the above mentioned areas of Russia it was taken that: R_x = 67 for Zhizdra district, R_x = 60 for Ulyanovo district and R_x = 26 for Khvostovici district. For Bragin district of Gomel region, Kostyukovichi and Krasnopol districts of Mogilev region the values of R_x were taken to be 29, 10 and 8.9, respectively.

If, preserving values of σ_{137}^x given in Table 4, the adopted values of ratios R are determined more precisely with actual data (for example, results of ^{129}I measurements in soil samples), most probably, a conclusion will have to be made concerning correction of initial values of individual doses of Class 1.

Anyway, even today two important factors become obvious which should be taken into account during the second iteration of thyroid dose reconstruction: possible later time of starting the grazing season and significant depositions of ^{131}I at later dates, for example, as was registered in Obninsk, Kaluga region [32].

Table 7

Characteristics of spreads of ratio of empirical values of mean internal thyroid doses D_i and doses D_∂ calculated using different models considered for some administrative districts on the contaminated territories of Belarus and Russia

Characteristics	Districts of Belarus[1]			Districts of Russia[2]		
σ^x_{137}, kBq/m^2	330	250	260	120	170	89
K_x, $mGy \cdot m^2/kBq$	0.59	0.21	0.19	1.4	1.3	0.54
Mean geometric value of ratio D_i/D_∂:						
Equation (5)	1.9	2.7	2.5	2.0	3.2	1.1
Equation (4)	1.5	26	22	7.7	13	1.6
Model developed in this work - (7, 8)	1.2	0.91	0.98	0.99	0.84	0.87
Standard geometric deviation of ratio D_i/D_∂ from 1:						
Equation (5)	3.6	1.6	2.9	3.0	2.8	2.6
Equation (4)	15	2.0	3.6	27	23	8.4
Model developed in this work - (7, 8)	1.7	1.4	1.6	1.5	1.4	1.5

[1] - Gomel region, outside the 30-km zone: 1 - Bragin, Mogilev region, 2 Kostyukovichi, 3 - Krasnopol;
[2] - Kaluga region of Russia: 1 - Zhizdra, 2 - Ulyanovo, 3 - Khvastovichi.

Figures 2 and 3 illustrate variations in the ratio of empirical values of doses and values calculated by different models. As is seen from these figures and Table 7 the proposed semiempirical model (7, 8) certainly gives a better agreement of calculation results and empirical values as compared with both models (4) and (5). Th pooled body of ratios of empirical to calculated values for more than 300 populated points of the contaminated areas in Belarus and Russia, with calculations by the semiempirical model is satisfactorily described by the lognormal function with median of 0.73 and standard geometrical deviation of 1.8. So, even today it can be acknowledged that the developed model, on a whole, have a good applicability. Of course, both the model itself and methods for implementing it in practice should be improved in future.

It would be appropriate to discuss the above mentioned issue of large values of parameter R_x for the contaminated areas of Kaluga region which appear to be accepted for matching our semiempirical model (7, 8) with empirical values of doses $D_{j,x}$. A similar situation is observed for Rechitsky and Loevsky districts of Belarus. In fact we had to introduce for these areas a systematic adjustment - a correction factor which is not necessarily related to abnormally high values of ratio $\sigma_{131}/\sigma_{137}$. The necessity of using such an adjustment is also dictated by some systematic factors which influenced Class 1 data for these areas.

First, for these areas the kinetics of ^{131}I may be essentially different from that assumed in the first calculations.

Second, as can be seen from the formal analysis of formula (7) the value σ^x_{137}, a mean ^{137}Cs deposition density on area X, may not have been determined correctly and the boundaries of this area may be at variance with boundaries of administrative districts. The values of $\sigma^{j,x}_{137}$ themselves are not completely identical and the physical meaning of these values should be understood when using them in the developed model.

As to obtaining additional results required for refining the model and based on measurements there are only two options: a more detailed information on deposition of ^{131}I and ^{137}Cs. The task of a more precise determination of ^{137}Cs deposition density is relatively simple. It is more difficult methodologically and more costly to solve the other problem of ^{131}I depositions using the only method suitable for this - measurement of the content of long-lived ^{129}I of the Chernobyl origin.

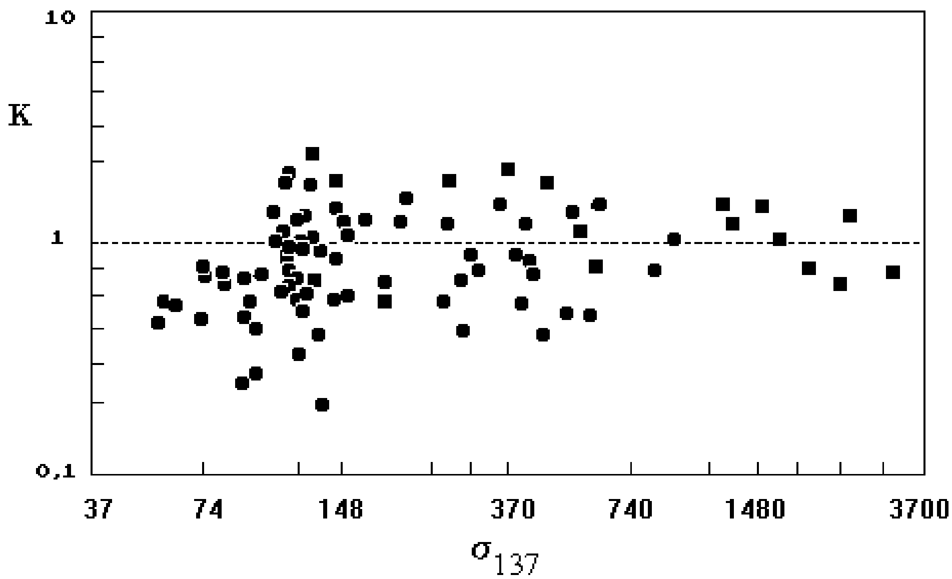

Fig. 2. Ratio of ***K*** (ordinate axis) of empirical values of internal thyroid doses (D_e) and estimates of doses (D_s) by semiempirical model (7, 8).
Abscissa axis - ^{137}Cs soil contamination density - σ^x_{137}, kBq/m^2.
Circles - data for Bragin district of Gomel region;
rectangulars - for Krasnopol district of Mogilev region of Belarus.

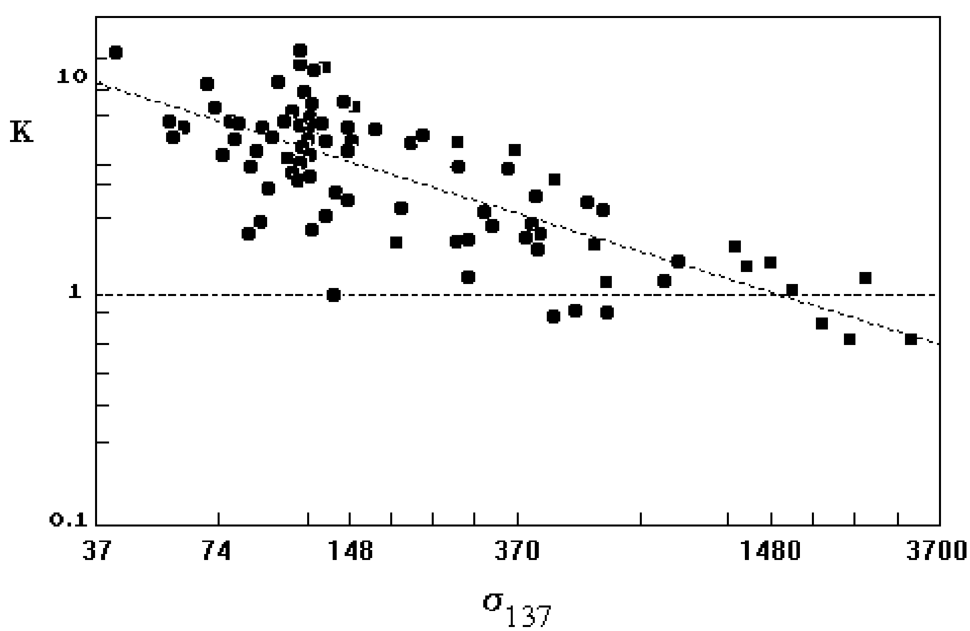

Fig. 3. Ratio of ***K*** (ordinate axis) of empirical values of internal thyroid doses (D_e) and estimates of doses (D_δ) by the proportional model (formula 4).
Abscissa axis - ^{137}Cs soil contamination density - σ^{x}_{137}, kBq/m^2.
Circles - data for Bragin district of Gomel region;
rectangular - for Krasnopol district of Mogilev region of Belarus.

A draft methodology has been prepared describing the procedure of calculation of internal thyroid doses based on determinations of ^{129}I in the area of interest. The formula to relate dose $D_{j,x}$ of internal thyroid exposure of adults in the ***j***-th populated point in area ***X*** using data on ^{129}I depositions $\sigma^{j,x}_{129}$ can be easily derived from formula (9) based on the initial ratio of activities of ^{131}I and ^{129}I in the reactor prior to the accident, which according to recommendations [32] are taken to be (5.0 ± 1.5)$\cdot 10^7$:

$$D_{j,x} = (1.8\sigma^{x}_{129} + 0.6\sigma^{j,x}_{129})\cdot e^{-0.086\cdot t}, \text{ Gy}, \quad (11)$$

where the mean deposition densities of ^{129}I in the ***j***-th populated point $\sigma^{j,x}_{129}$ and area ***X*** σ^{x}_{129} are expressed in Bq/m^2;

the exponential factor provides for change in ratio ^{131}I/^{129}I in time ***t*** (day) after the reactor explosion prior to the effective "moment" of radioiodine depositions on area ***X***.

Therefore, by formula (11) two major problems should be solved: 1 - the values σ^{x}_{129} and $\sigma^{j,x}_{129}$ need to be determined with a required accuracy and 2 - effective value of time ***t*** should be determined. The first problem, in fact, is the base for optimum design of direct measurements of ^{129}I in the environment in conjunction with methods of extrapolation-interpolation of data on ^{137}Cs deposition density.

5. Estimation of mean and collective doses

Table 8 contains mean and collective thyroid doses calculated with the described semiempirical model for population of different regions of Russia living in the areas with ^{137}Cs soil contamination density more than 3.7 kBq/m^2. It also includes data on expected thyroid cancers due to internal exposure to iodine radionuclides for different age groups.

It should be pointed out that the values of collective doses in Table 8 are somewhat different from estimates published earlier for Kaluga and Bryansk regions based on results of direct measurements [3, 8, 13]. This is because the model discussed in this paper uses, as was mentions, a large volume of initial data for different regions (about 160 thousand measurements) and naturally smoothes possible systematic differences associated with calculation of doses in specific regions. Possible sources of such discrepancies are discussed in section 4.

Calculations of expected number of thyroid cancers during the whole life since the exposure time are made based on the following age and sex dependencies of the radiation risk coefficient [33]:

- the annual risk of thyroid cancer at the age to 18 years is 2.5 cases per 10000 persons-Gy, given external acute X-ray or β-, γ-irradiation, the radiosensitivity of adults being lower by a factor of two than in children and adolescents and efficiency of internal ^{131}I exposure is lower by a factor of three than in the indicated cases of acute external exposure;
- rediosensitivity of female population is twice as high as that of male;
- the probability of annual manifestation of radiation-induced thyroid cancers is approximately the same for the whole remaining life period after a minimum five years latent period of the disease development.

It should be borne in mind that additional number of radiogenic thyroid cancers can result from exposure of a specific organ to external γ-irradiation (and due to internal irradiation with cesium radionuclides). We have estimated the value of additional collective dose of thyroid exposure due to external γ-irradiation. This estimate is for the dose accumulated for 9 years after the accident, i.e. April 1995. For the contaminated areas of eight regions of Russia indicated in Table 2 this value is $25.9 \cdot 10^3$ man-Sv, among them for Bryansk region $11 \cdot 10^3$ man-Sv, respectively. This can lead to additional 77 cases of radiogenic thyroid cancers (of them 65 - for persons younger than 18 at the exposure time). In Bryansk region one can expect 33 additional cancer cases, of them 28 in persons before 18 years at the exposure time. It should be remembered that the exposure dose accumulated in the whole time period after the accident can exceed the dose accumulated in 9 years after the accident. Correspondingly, the additional number of cancers expected due to this can exceed the above estimates.

The estimate of additional external thyroid dose accumulated over 9 years has been derived using the data obtained by EPR-dosimetry with tooth enamel [34]. In doing this use was made of results of EPR-dosimetry of samples of tooth enamel in 442 adults living in 23 populated points of five districts of Belarus with ^{137}Cs soil contamination density from 220 to 766 kBq/km^2 [35, 36] and in uncontaminated areas of two districts of Kaluga region. The results of measurements were adjusted for each individual for contribution of natural background exposure during life time to the time of tooth extraction. This contribution (by EPR-measurements of tooth enamel in population of uncontaminated areas) is $(0.12 \pm 0.02) \cdot 10^{-2}$ Sv/year. Besides, account was taken of the adjustment for background signal due to the method used for EPR-dosimetry. This adjustment established based on results of international intercalibration is (7.5 ± 0.5) 10^{-2} Sv [37]. As a result, a correlation has been derived between dose accumulated for 9 years since the accident D_9^{ext} and ^{137}Cs soil contamination density (the correlation coefficient is 0.82):

Table 8

Thyroid doses in different regions of RF and estimated expected number of thyroid cancers due to internal exposure of thyroid to iodine radionuclides following the Chernobyl accident

<D> is mean absorbed thyroid dose for the population;
KD is collective thyroid dose for the whole population of the area.

Contamination density range ^{137}Cs, kBq/m^2	Population, thousand	σ^x_{137}, kBq/m^2	***<D>***, mGy	***KD***, 10^3 persons-Gy	Expected radiogenic thyroid cancers by age groups*): < 18	≥ 18	Alll ages
Bryansk				94.34			
3.7 - 37	670.0**)	12.6	12.4		21	4	25
37- 185	227.0	86.6	76.5		44	8	52
185 - 555	147.0	336	229		85	15	100
> 555	93.1	918	376		88	15	103
all cont. areas					238	42	280
Tula				92.34			
3.7 - 37	370.0**)	24.4	30.6		29	6	35
37- 185	770.0	112	77.4		150	26	176
185 - 555	170.0	281	126		54	9	63
all cont. areas					233	41	274
Kaluga				10.12			
3.7 - 37	120.0***)	20.3	28.4		9	1	10
37- 185	78.0	98.4	65.5		13	2	15
185 - 555	15.5	263	103		4	1	5
all cont. areas					26	4	30
Orel				21.37			
3.7 - 37	100.0***)	23.3	22.6		6	0	6
37- 185	330.0	90.3	54.5		45	8	53
185 - 555	18.0	220	95.1		4	0	4
all cont. areas					55	8	63
Kursk				5.80			
3.7 - 37	110.0***)	21.1	17.0		5	0	5
37 - 185	134.0	59.6	29.3		10	2	12

all cont. areas					15	2	17
Ryazan’				9.22			
3.7 - 37	110.0***)	26.6	27.1		7	1	8
37- 185	182.0	64.4	34.3		16	3	19
all cont. areas					23	4	27
Leningrad				0.544			
3.7 - 37	10.0***)	29.2	24.0		1	0	1
37- 185	19.5	49.9	27.9		1	0	1
all cont. areas					2		2
Total				233.734	592	103	695

*)-rounded off to integral numbers;
**)-approximate estimate of the population taking into account regional centres;
***)-approximate estimate of the population.

$$D_9^{ext} = (6.76 \pm 0.8)\cdot 10^{-5} \cdot \sigma_{137},\ 3_{в},(12)$$

where σ_{137} is ^{137}Cs soil contamination density in a populated point, kBq/m^2.

It should be said that the above external radiation dose may be an overestimation by a factor of 1.5, considering the factor of “ hardness of tooth detector” due to the input from scattered radiation (estimation of this factor can be found in [38]).

Table 9 demonstrates results of analysis of frequency of thyroid cancers in children and adolescents detected since 1990 in the Bryansk region (under 18 years in April-May 1986) as a function of mean ^{137}Cs contamination of different areas of the region and the value of mean thyroid dose for the same areas. The thyroid doses calculated with the described semiempirical model are given for the adult population, doses for other age categories can be estimated using the relations from work [27].

Data of Table 9 demonstrate an increase in frequency of detected thyroid cancers per 100 thousand children and adolescents of this age at exposure time and living in the areas with mean ^{137}Cs soil contamination level in the ranges (3.7-37), (37-185) and above 185 kBq/m^2 respectively as a function of thyroid exposure level.

Table 9

Frequency of detected thyroid cancers in children and adolescents from the contaminated areas of Bryansk region depending on exposure level

σ_c **(**σ_{min} **-** σ_{max}**)** is mean (minimum - maximum) ^{137}Cs contamination density of the populated point in which residents were diagnosed thyroid cancers;
D_c **(**D_{min} **-** D_{max}**)** is mean, minimal and maximum thyroid doses in adults of the populated points in which thyroid cancers were detected;
$N_{<18}$ is population at the age younger 18 in 1986;
$C_{<18}$ is number of detected thyroid cancers for persons younger 18;
$C_{<18}/N_{<18}$ is frequency of detected thyroid cancers for persons younger 18 per 100000 people younger 18.

Measured σ_{137} on the area, kBq/m^2	σ_c (σ_{min} - σ_{max}), kBq/m^2	D_c (D_{min} - D_{max}), mGy *)	$N_{<18}$, thousand	$C_{<18}$	$C_{<18}/N_{<18}$, case/100000 persons
3.7 - 37	14.4 (12.6 - 33.7)	5.7 (3.1 - 13.3)	218.6	26	11.9
37 - 185	83.6 (50.7 - 137)	33.3 (20 - 69)	48.9	8	16.3
more than 185	466 (295 - 640)	135 (118 - 253)	44.2	13	29.4

* - coefficients for recalculation of absorbed doses in children and adolescents from absorbed doses in adults are presented in [10, 12, 14].

6. Estimation of individual doses

In order to pass from mean doses to individualised estimates results of special polling were used. The results of polling conducted in 1990-1994 include data on age, sex of the examined, arrival and departure time, movement after the accidental contamination with indication of addresses (particular details for April-May 1986), information about iodine prophilaxis and protection measures, if any. Also, questions were asked concerning milk diet prior to the accident, in April-May 1986 and afterwards. Detailed information was obtained on consumption of both centrally supplied and home made food, including unskimmed milk, sour milk, milk soups, porridge. In case of pregnancy and breast feeding features of feeding infants were specified. The result of individual reconstruction of doses of thyroid exposure to iodine radionuclides is the value of most probable individual dose with indication of probabilities of upper and lower bounds of individual dose. The statistical characteristics of individual dose distributions are obtained from the statistical analysis described in works [17, 18].

Results of estimation of individualised absorbed thyroid doses are presented in Table 10.

Retrospective estimates of individual thyroid doses have been derived for thirty children and adolescents (age at exposure time) from forty eight persons diagnosed thyroid cancer and living on the contaminated areas of Bryansk region in May-June 1986 [39]. These estimates are needed for more accurate determination of radiation risk using the “case-control” method of epidemiological analysis.

In 14 of 30 cases (47%) the most probable values of individual doses were in the range from 200 to 2700 mGy and in the rest 53% cases - 50mGy and less. 6 children were administered stable iodine after 10 May, and 12 - underwent multiple additional X-ray examinations. Within 85% confidence interval the minimum values of reconstructed individual doses were about 0.33 of the most probable value and the maximum values - about 1.6 of the most probable value.

It is pertinent to note that the typical distribution of individual doses for the total population of children living in the contaminated areas, but not diagnosed thyroid cancer is different - for most children absorbed thyroid doses are below 200 mGy and a smaller part of it - more than 200 mGy.

Table 10

Results of reconstruction of individual thyroid doses from iodine radionuclides for children and adolescents of Bryansk region diagnosed thyroid cancer

S is patient sex; ***Y*** is year when thyroid cancer was diagnosed;
σ_{137} is mean ^{137}Cs contamination density for a point of residence of a patient in May - June 1986;
D_{pr} is most probable value of thyroid absorbed dose;
A_i is attribute of iodine prophylaxis: " +" - yes; " -" - no;
M is additional exposure due to medical procedures.

N	Patient	*S*	Birth date	Area of residence in May - June 1986	σ_{137}, kBq/m^2	D_{pr}, mGy	A_i	*Ì*	*Y*
1	B.I.A.	f	10.03.79.	Novozybkov	573	1400	+	-	1994
2	Zh.A.P.	m	26.06.83.	Novozybkov	573	900	?	-	1994
3	S.A.P.	f	03.12.85.	Novozybkov	573	2400	+	-	1994
4	B.E.A.	f	12.09.84.	Novozybkov	340	900	?	-	1993
5	Zh.A.P.	m	26.04.83.	Novozybkov	718	800	+	-	1994
6	P.E.V.	f	29.04.78.	Novozybkov	729	400	+	-	1994
7	K.I.V.	f	01.11.84.	Novozybkov	340	1600	+	-	1993
8	Zh.A.V.	m	04.07.72.	Klintsy	148	200	-	-	1991
9	N.N.N.	f	28.06.84.	Klintsy	104	1000	-	+	1990
10	Ch.O.Yu.	f	12.09.85.	Klintsy	85.1	700	-	-	1992
11	M.A.V.	m	09.05.84.	Klintsy	104	1000	-	-	1993
12	B.M.A.	f	18.02.86.	Klimovo	141	200	-	-	1992
13	L.Yu.B.	f	08.07.86.	Starodub	70.3	<20	-	+	1992
14	G.E.M.	f	03.05.68.	Dyat'kovo	26.6	20	-	+	1993
15	K.V.I.	m	13.09.71.	Surazh	10.7	<10	-	+	1990
16	K.S.V.	f	07.05.68.	Trubchevsk	55.5	20	-	+	1992
17	L.O.V.	m	25.10.76.	Vygonichi	24.8	20	-	+	1994
18	V.E.V.	f	08.10.70.	Karachev	20.7	<10	-	+	1992
19	A.E.Yu.	f	26.11.73.	Karachev	20.7	<10	+	+	1993
20	B.S.A.	m	28.01.77.	Suzem	18.5	<10	-	+	1990
21	N.A.V.	m	02.09.77.	Komarichi	32.6	<10	-	+	1993
22	Z.O.N.	f	15.08.77.	Seltso	9.25	50	-	-	1994
23	P.O.G.	f	07.09.78.	Navlino	40.7	35	-	-	1994
24	B.A.A.	m	14.08.71.	Bryansk	12.6	<10	-	-	1992
25	K.A.A.	m	29.11.73.	Bryansk	12.6	<10	-	+	1992
26	E.(Shch)T.P.	f	28.07.78.	Bryansk	12.6	20	-	-	1993
27	Ts.N.Yu.	f	29.09.73.	Bryansk	12.6	10	-	+	1991
28	Yu.A.L.	m	12.05.78.	Bryansk	12.6	<10	-	-	1994
29	Ch.I.K.	f	15.02.86.	Novozybkov	529	2700	-	-	1994
30	K.S.A.	f	03.06.73.	Trubchevsk	17.4	10	-	+	1994

Conclusion

1. The developed semi-empirical model of extrapolation-interpolation type has some important advantages compared to other models of such type and allows estimation of internal thyroid dose with the accuracy characterized by standard geometric deviation of about 1.8.

2. The available data on individual internal thyroid dose estimated based on direct measurements, which still need to be refined have made it possible to compare average thyroid exposure levels with average contamination levels and make generalizatons to derive retrospective estimates of thyroid doses for the population of the contaminated areas, given missing data of dosimetric survey of thyroid. These estimates are considered as results of the first iteration in development of practical methods of thyroid dose reconstruction.

3. Using the proposed model, collective and mean doses have been calculated for different regions of Russia and predictions were made for radiogenic thyroid cancers. In conjunction with data of individual questionnaires the model allows estimation of individualized doses for persons diagnosed thyroid cancer. Such estimates have been derived for 30 diagnosed thyroid cases.

4. Work is now under way to continue retrospective estimates of individual thyroid doses for persons with diagnosed

thyroid pathology. Special attention is given to factors which can result in additional adjustment of exposure dose values: rainfall or its absence in populated points in late April-early May 1986, the beginning of grazing season in this area in 1986, individual protection measures or their absence in the acute period after the accident, pathology of thyroid influencing its weight and iodine metabolism intensity etc. Soil samples are being collected and saved to be analysed for long-lived ^{129}I of the Chernobyl origin as an indicator of ^{131}I deposited on these areas in 1986. Consideration of these factors can diminish the range of uncertainties for retrospective estimates of mean and individual doses.

References

1. **Okeanov A.E., Dimidchik E.P., Ankudovich M.A. et al.** Thyroid cancer in Republic of Belarus before and after the Chernobyl accident. - Document of WHO/EOS/94.26. - Geneva, 1994 (in Russian).
2. **Tsyb A.F., Parshkov E.M., Shakhtarin V.V. et al.** Characterization of thyroid pathology in children and adolescents of the most contaminated areas of Bryansk region of Russia after the Chernobyl accident. - Document of WHO/EOS/94.15. -Geneva, 1994 (in Russian).
3. **Stepanenko V.F., Tsyb A.F., Matveenko E.G. et al.** Thyroid exposure doses among the population of contaminated territories: methodology and results of measurements. Deutsch - russische Konferenz fur Messprogramm in Russland. - Moskau, 1992. - S. 53 - 59.
4. **Khrushch V.T., Gavrilin Yu.I., Konstantinov Yu.O. et al.** Characterization of inhalation intake of radionuclides. Medical aspects of the Chernobyl accident. Proceedings of scientific conference on 11-13 May 1988, Kiev. - Kiev: Zdorov'ya, 1988. - P. 76-87 (in Russian).
5. Exposure resulting from the Chernobyl accident. Proceedings of the 37th session of UN SC. -Vienna, 6-17 June 1988 (in Russian).
6. **Gavrilin Yu.I., Gordeev K.I., Ivanov V.K. et al.** Specific features and results of determinations of internal thyroid doses for the population of contaminated areas of Republic of Belarus. Bulletin of USSR AMS. - 1992. - N 2. - P. 35-43 (in Russian).
7. **Romanenko A.E., Likhtarev I.A., Shandala N.K. et al.** Hygenic estimation of thyroid doses in the population of UkrSSR after the Chernobyl accident. Bulletin of USSR AMS. - 1991. - N 8. - P. 44-47 (in Russian).
8. **Zvonova I.A., Balonov M.I.** Radioiodine dosimetry and prediction of consequences of thyroid exposure of the russian population following the Chernobyl accident. The Chernobyl papers, vol. 1. - Richland, Washington, 1993. - P. 71-126.
9. **Likhtarev I.A., Shandala N.K., Gulko G.M. et al.** Ukrainian thyroid doses after the Chernobyl accident. Health Phys. - 1993. - N. 64 (6). - P. 594-599.
10. **Gavrilin Yu.I. Khrushch V.T., Shinkarev S.M.** Reconstruction of internal thyroid dose for the population of the areas of Republic of Belarus contaminated after the Chernobyl accident. (State of work and important future tasks). Abstracts of presentations at the 3-d republic. conference, Gomel, 15-17 April 1992. - Part 1. - P. 75-78 (in Russian).
11. **Gavrilin Yu.I., Khrushch V.T., Shinkarev S.M. et al.** Exposure of thyroid with radioiodine in the population of Belarus as a result of the Chernobyl accident. Papers of conference " Nuclear energy and human safety" . - Nizhny Novgorod, part 1, p. 222-224 (in Russian).
12. **Tsyb A.F., StepanenkoV.F., Gavrilin Yu.I. et al.** Problems of retrospective estimation of exposure doses of population as a result of the Chernobyl accident: features of formation, structure and exposure levels from direct measurements. Part 1: Doses of internal exposure of thyroid. - Document of WHO/EOS/94.14. - Geneva, 1994 (in Russian).
13. **Tsyb A.F., Stepanenko V.F., Matveenko E.G. et al.** Structure and thyroid exposure levels in the population of the contaminated areas of the Kaluga region. Radiation and Risk. - 1994. - Issue 4. - P. 129-135 (in Russian).
14. **Aref'eva Z.S., Bad'in V.I., Gavrilin Yu.I. et al.** Guidelines on thyroid dose estimation with human intake of radioactive isotopes of iodine. Ed.

by L.A.Il'in. - M.: Energoizdat, 1988. - 80 p. (in Russian).

15. **Gavrilin Yu.I., Khrushch V.T., Shinkarev S.M. et al.** Generalization of results of reconstruction of internal thyroid doses. Establishing associations between parameters of contamination of residential areas with thyroid exposure levels. - Report of IBPh, Moscow, 1993. - 110 p. and 819 p. of attachment (in Russian).
16. **Pitkevich V.A., Shershakov V.M., Duba V.V. et al.** Reconstruction of radionuclides composition of depositions on the territory of Russia as a result of the Chernobyl accident. Radiation and Risk. - 1993. - Issue 3. - P. 62-93 (in Russian).
17. **Gavrilin Yu.I., Khrushch V.T., Shinkarev S.M. et al.** Passportization of populated points for the areas of Gomel region within the strict control zone. - Report of IBPh, 46-17-91/91, B-91-3. - M., 1991. - 75 p. (in Russian).
18. **Gavrilin Yu.I., Khrushch V.T., Shinkarev S.M. et al.** Determination of individual and collective characteristics of thyroid exposure by refined models accounting for dynamics of area contamination and radioiodine intake, considering data of personal polling of residents of Republic of Belarus: Report of IBPh on stage N 4, N 7-17/93. - M., 1993. - 51 p. (in Russian).
19. **Gavrilin Yu.I., Khrushch V.T., Shinkarev S.M. et al.** Characterization of input of short-lived radionuclides to internal thyroid exposure in the population of areas of BSSR contaminated after the Chernobyl accident. Report of IBPh 46-17/91, B-91-3. - M., 1991. - 128 p. (in Russian).
20. **Yook C.N., Lynn R. Anspaugh and Richard T. Cederwall.** ORERP internal dose estimates for individuals. Health Phys. - 1990. - Vol. 59, N 5 (November). - P. 693-713.
21. **Gavrilin Yu.I., Khrushch V.T., Shinkarev S.M. et al.** Internal thyroid exposure for the population of some areas of Belarus. Medical Radiology. - 1993. - N 6. - P. 15-19 (in Russian).
22. **Dunning D.E., Schwarz G.** Health Phys. - 1981. - Vol. 40. - P.661-675 (in Russian).
23. **Gavrilin Yu.I., Khrushch V.T., Shinkarev S.M. et al.** Verification of dosimetric data and reconstuction of individual thyroid doses for the population of Minsk: Report of IBPh. - M., 1991. - 25 p. (in Russian).
24. **Avramenko T.A., Drozdovich V.V., Minenko V.F. et al.** Catalogue of exposure doses of residents of populated points of Republic of Belarus. - Minsk, 1992. - 94 p. (in Russian).
25. Handbook on the radiation situation and exposure doses in 1991 for population of Russian Federation affected by radioactive contamination as a result of the Chernobyl accident. Ed. by M.I.Balonov. - St.-P., 1993 (in Russian).
26. **Dubina Yu.V., Shchekin Yu.K., Guskina L.N.** Classification and verification of data of spectrometric analysis of samples of soil, grass, milk and diary products with measured ^{131}I level. - Minsk, 1990 (in Russian).
27. **Aref'eva Z.S., Bad'in V.I., Gavrilin Yu.I. et al.** Estimation of absorbed thyroid dose from iodine radioisotopes for persons exposuded to radiation as a result of the Chernobyl accident: Guidelines. - M., 1987 (in Russian).
28. **Buldakov L.A.** Method for reconstruction of thyroid dose from incorporated ^{131}I. Medical Radiology. - 1993. - N 6. - P. 20-24 (in Russian).
29. **Hoffman F.Owen, Thiessen Kathleen M., Frank Marilyn L. and Blaylock B.Gordon.** Quantification of the interception and initial retention of radioactive contaminants deposited of pasture grass by simulated rain. Atmospheric Environment. - 1992. - Vol. 26A, No.18. - P. 3313-3321.
30. **Muller H. and Prohl G.** ECOSYS-87: A dynamic model for assesing radiological consequences of Nuclear accidents. Health Phys. - 1993. - Vol. 64, N 3 March. - P. 232-252.
31. Guidelines on calculation of individual and collective doses of population from radionuclides releases to the atmosphere during operaition of NPP. PNAE, G, direction 2. Guidelines of rules and norms on radiation safety in nuclear power industry. - M., 1989. - P. 19-315 (in Russian).
32. **Makhon'ko K.P., Kozlova E.G.** Calculation of ^{131}I accumulation on soil and distribution of doses from its gamma-irradiation on the territory of USSR

contaminated after the Chernobyl accident. - Report of IEM SPA " Typhoon" of USSR Roshydromet, N 7028, Obninsk, 1990, 267 p. (in Russian).

33. National Council on Radiation Protection and Measurements, Induction of thyroid cancer by ionizing radiation, Bethesda, MD: NCRP; NCRP Report N 80, 1985.

34. **Ivannikov A.I., Skvortsov V.G., Stepanenko V.F. et al.** Potential of EPR-dosimetry by tooth enamel for reconstruction of external doses in liquidators of the Chernobyl accident. Physical Medicine. - 1992. - V. 1, Issue 3-4 (in Russian).

35. **Skvortsov V.G., Ivannikov A.I., Tsyb A.F. et al.** Results of surveys by EPR-dosimetry for the population of contaminated South-Western areas of Bryansk region. - Document of WHO/EOS /94.12. - Geneva, 1994 (in Russian).

36. **Skvortzov V., Ivannikov A., Stepanenko V. et al.** Regularities in distribution of individual doses for population of radioactive contaminated territories measured by tooth enamel EPR-spectroscopy. Proc. of 4-th International Symposium on ESR Dosimetry and Applications. GSF, Munchen/Neuherberg, May 15-19, 1995. - P. 214.

37. **Chumak V., Baran N., Bugai A. et. al.** The first international intercomparison of EPR-Dosimetry with teeth: first results. Ibid p.197.

38. **StepanenkoV.F., Skvortzov V.G., Kondrashov A.E. et al.** ESR and TL dosimetry Systems: comparative measurements for human phantom. Ibid. p. 250.

39. **Parshkov E.M., Tsyb A.F., Stepanenko V.F.** Analysis of thyroid pathology and thyroid cancers in children and adolescents affected by a iodine impact as a result of the Chernobyl disaster. Radiological, medical and socio-economic consequences of the Chernobyl accident. Rehabilitation of territories and population. Abstracts of presentations at conference on 21-25 May 1995, Golitsino, 1995. - Moscow, 1995. - P. 57 (in Russian).