Appendix 2

Post - Chernobyl Thyroid Doses in Belarus Based on Measurements of the ^{131}I Activity in the Human Thyroid and on the Semi – Empirical Model

Post - Chernobyl Thyroid Doses in Belarus Based on Measurements of the ^{131}I Activity in the Human Thyroid and on the Semi – Empirical Model

S. Shinkarev and Y. Gavrilin

All-Russian Public Organization of Invalids "Chernobylets",

Scientific Center "FENIX", Moscow, Russia

Moscow

February 2004

OBJECTIVES

The main purpose for FENIX in the current project was to provide the realistic age-dependent thyroid dose estimates for the Belarusian children exposed as a result of the Chernobyl accident occurred on April 26, 1986.

The main tasks for FENIX were as follows:

- Critical examination and consistency checks of individual thyroid dose estimates. Revision of individual thyroid doses where necessary;
- Estimation of average age-dependent thyroid doses and associated uncertainties in thyroid doses for Belarusian settlements with more than 10 measurements of ^{131}I-activities in human thyroids after the Chernobyl accident, that are considered to be representative to characterize thyroid exposure to the residents;
- Application of the generalized model (semiempirical model) developed by FENIX to provide age-dependent thyroid dose estimates and associated uncertainties in Belarusian settlements, including those for which no direct thyroid measurements are available;
- Estimation of average age-dependent thyroid doses for the children population in each of the Belarusian oblasts;
- Comparative analysis together with the Belarusian Research and Clinical Institute of Radiation Medicine and Endocrinology and German GSF - Institute of Radiation Protection of age-dependent thyroid dose estimates obtained by using different approaches for the considered Belarusian settlements and oblasts.

MATERIALS AND METHODS

Input data used in the project were as follows:

- database with individual measurements of the ^{131}I thyroidal content carried out within a few weeks following the Chernobyl accident and subsequent estimates of individual thyroid doses based on those thyroid measurements using corresponding functions of the ^{131}I intake for about 130,000 Belarusian inhabitants (description of the database is presented in ANNEX 1);
- database of ^{137}Cs ground deposition densities for all Belarusian settlements prepared by BelHydromet;
- database of the results of spectrometric measurements of various radionuclides, including ^{131}I, in environmental samples and foodstuffs carried out in May through July 1986, prepared by the Institute of Biophysics (Moscow);
- demographic data on Belarus.

The main methods developed outside the framework of the project but used in the project were as follows:

- method to assess individual thyroid doses for the Belarusian people on the basis of the results of individual ^{131}I thyroidal content (description of the method is presented in ANNEX 2);
- semi-empirical method to assess age-dependent average thyroid dose estimates in Belarusian settlements where no direct thyroid measurements were conducted within a few weeks following the accident (description of the method is presented in ANNEX 3).

WORK PERFORMED IN THE PROJECT AND RESULTS

Critical examination of individual thyroid dose estimates was done in order to check whether the estimates of thyroid doses available in data bank are consistent. Such analysis revealed inconsistency in the data related to the residents of Gomel city. Special work was conducted to revise individual thyroid doses of the residents of Gomel city. Detail description of the work and the results of revision of individual and average thyroid doses are presented in the report “Re-evaluation of the estimates of age-dependent average doses for the residents of Gomel city” (ANNEX 4). Also, additional analysis of the direct thyroid measurements for children from Minsk city was done. On the basis of the revision of individual and average thyroid doses for inhabitants of Gomel and Minsk cities the draft of the paper “Thyroid dose assessment for the population of Minsk and Gomel cities in Belarus as a result of the Chernobyl accident: Part 1 – Minsk city” was prepared (ANNEX 5).

Analysis of the individual thyroid doses available in the data bank showed that for 331 persons thyroid doses exceeded 10 Gy. Taking into account that high doses have significant influence on average thyroid dose estimates in the settlement, it was decided to investigate whether the “measured” doses exceeding 10 Gy were realistic. This work had been done before the following step in the project to calculate average age-dependent doses for the settlements was conducted. Detail description of this investigation was written in the report “The problem of doses exceeding 10 Gy (Analysis of the Belarusian databank)”. Based on the materials of this report, the draft of the paper “Reliability of assessment of the individual thyroid doses greater than 10 Gy for the Belarusian population based on in-vivo monitoring of iodine-131 activity in human thyroids following the Chernobyl accident” was prepared (ANNEX 6). The main conclusion of this investigation was as follows. Number of doses exceeding 10 Gy looks realistic. The high thyroid dose estimates should be used in the calculation procedure to assess average age-dependent thyroid doses for the settlements with direct measurements.

In order to realize one of the key tasks in the project to assess average age-dependent thyroid doses and associated uncertainties in thyroid doses for Belarusian settlements with more than 10 measurements of ^{131}I-activities in human thyroids a special methodology was developed. Detail description of this methodology is presented in the report "Methodology of assessment of age-dependent average thyroid doses for the settlements in Belarus" (ANNEX 7).

The results of estimates of average age-dependent thyroid doses and associated uncertainties in thyroid doses for Belarusian settlements with more than 10 measurements of ^{131}I-activities in human thyroids are presented in file "Belarus-settlements-doses.xls". The form of presentation of those results is available in ANNEX 8.

Estimation of average age-dependent thyroid doses for the children population in each of the Belarusian oblasts was done calculating the average age-dependent thyroid dose estimates for the settlements using (1) direct thyroid measurements if a given settlement had more than 10 measurements of ^{131}I-activities in human thyroids and (2) semi-empirical method if no or less than 10 measurements of ^{131}I-activities in human thyroids were available for a given settlement. The results of estimation of average age-dependent thyroid doses for the children population in each of the Belarusian oblasts are presented in ANNEX 9.

CONCLUSION

The main results of the work performed by FENIX in the current project are the estimates of average age-dependent doses for the children populations living

1) in the settlements with more than 10 measurements of ^{131}I-activities in human thyroids and
2) in each of the six Belarusian Oblasts.

Those estimates were an important input to derive the estimates of thyroid cancer incidence rates for Belarus in the project.

Important intermediate results were

1) revision of individual and average thyroid dose estimates for the populations of the cities of Gomel and Minsk;

2) justification of necessity to account for high thyroid dose estimates under calculation of average age-dependent thyroid doses for the settlements with direct thyroid measurements.

During implementation of the project four research reports considering various issues discussed in the framework of the project and the drafts of two papers have been prepared.

Acknowledgement

This work has been supported by the German Federal Minister of Environment, Nature Preservation and Reactor Safety and the German Federal Office of Radiation Protection under contract number StSch 4240

ANNEX 1

DESCRIPTION OF THE DATABANK WITH INDIVIDUAL THYROID DOSE ESTIMATES BASED ON DIRECT THYROID MEASUREMENTS

On the basis of developed methods individual thyroid doses have been estimated and the data bank for the approximately 130,000 Belarusian people has been formed. Table 1 presents the geographical distribution of the dose estimates included in the dosimetry data bank.

Table 1. Characteristics of the data bank of individual thyroid dose estimates for the Belarusian people.

Territories	Number of persons with dose estimates with percentage of the population in parentheses		
	children up to 18y	adults	total
Gomel Oblast			
Three south raions: Bragin, Khoiniki, and Narovlya	17557 (61%)	48778 (59%)	66335 (60%)
Two raions: Loev and Rechitsa	5257 (14%)	9299 (8.4%)	14556 (10%)
Three northeastern raions: Buda-Koshelev, Korma, and Vetka	1947 (6.5%)	2324 (2.7%)	4271 (3.7%)
Gomel City	2249 (1.8%)	3364 (1%)	5613 (1.2%)
Mozyr City	705 (3%)	765 (1%)	1470 (1.5%)
Total for Gomel Oblast	*27715*	*64530*	*92245*
Mogilev Oblast			
Five raions: Chericov, Klimovichi, Kostyukovichi, Krasnopolye, and Slavgorod	4377 (12%)	8491 (8%)	12868 (9%)
Mogilev City	197 (0.2%)	910 (0.3%)	1107 (0.3%)
Total for Mogilev Oblast	*4574*	*9401*	*13975*
Minsk Oblast			
Minsk City	7211 (1.9%)	12830 (1.1%)	20041 (1.3%)
TOTAL	**39500**	**86761**	**126261**

It follows from Table 1 that the main part of dose estimates (about 75% of total in the bank) are the estimates obtained for the inhabitants of Gomel Oblast, including the estimates for the residents of the three southern raions: Bragin, Khoiniki, and Narovlya (about 53% of total in the bank). It should be noted a high percentage (60%) of the population measured in the three mentioned raions.

The information on median and arithmetic mean values of individual dose estimates for the inhabitants in some areas of Belarus as well as the distributions of individual dose estimates for children up to 18 y (at the time of the accident) and adults are presented in Table 2. It is seen that the highest thyroid exposure was realized for the inhabitants of the evacuated (before May 5, 1986) villages in Bragin, Khoiniki, and Narovlya raions. Exposure to thyroids for urban population, on average, is significantly lower than that for rural population.
Analysis of the distributions of individual thyroid dose estimates for different age-groups and settlements revealed that the major of them are satisfactorily described with the log-normal function. Fig.1 illustrates the distribution of the individual thyroid doses (D_{1i}) for the adult population (N=656) of Pogonnoe village in Khoiniki raion in Gomel Oblast.

The upper figure (Fig.1a) presents the distribution of individual thyroid doses and the lower one (Fig.1b) presents the distribution of natural logarithms of individual thyroid doses. It is observed that the distribution of $\ln(D_{1i})$ is close to normal. The calculation method to test whether the distribution of the values of $\ln(D_{1i})$ can be described satisfactorily with normal function showed that asymmetry coefficient was estimated to be equal to 0.10 (standard error was estimated to be equal to 0.10) and eccess was estimated to be equal to -0.066 (standard error was estimated to be equal to 0.19). That confirms the possibility to use lognormal function to describe the distribution of individual thyroid dose for adult population of Pogonnoe village.

ESTIMATES OF THE CONTRIBUTION OF SHORT-LIVED RADIOIODINES TO THYROID EXPOSURE

Relative contribution of short-lived radioiodines to absorbed internal thyroid dose (expressed as ratios of ^{131}I thyroid dose) for the Belarusian inhabitants in the areas where direct measurements had been conducted were estimated as follows:

- 10 to 40% for urban and rural residents who did not consume milk (only inhalation intake); and
- 1 to 6% for rural residents who consumed locally produced milk.

Table 2. Levels of thyroid exposure to the inhabitants in some areas of Belarus where direct thyroid measurements were conducted.

Areas	Age-group	Median, Gy	Arithmetic mean. Gy	Fraction of people (%) with doses D_i in the range, Gy:				
				$D_i \leq 0.3$	$0.3 < D_i \leq 1$	$1 < D_i \leq 3$	$3 < D_i \leq 10$	$D_i > 10$
Evacuated villages (before May 5, 1986) in Bragin, Khoiniki, and Narovlya in Gomel Oblast	children up to 18 y	1.4	2.9	14.97%	25.78%	32.98%	20.84%	5.43%
	adults	0.54	0.92	32.85%	39.09%	23.00%	4.89%	0.17%
Non-evacuated villages (before May 5, 1986) in Bragin, Khoiniki, and Narovlya in Gomel Oblast	children up to 18 y	0.63	1.4	28.06%	36.61%	24.88%	9.02%	1.43%
	adults	0.20	0.37	63.35%	28.68%	7.30%	0.66%	0.01%
Villages in Rechitsa and Loev raions in Gomel Oblast	children up to 18 y	0.46	0.86	32.12%	45.46%	17.82%	4.41%	0.19%
	adults	0.15	0.29	70.75%	24.62%	4.63%	-	-
Villages in northeastern raions of Gomel Oblast: Buda-Koshelev, Korma, and Vetka	children up to 18 y	0.45	1.0	38.76%	32.77%	22.00%	5.72%	0.75%
	adults	0.10	0.21	82.53%	14.78%	2.69%	-	-
Five raions of Mogilev Oblast: Chericov, Klimovichi, Kostyukovichi, Krasnopolye, and Slavgorod	children up to 18 y	0.14	0.28	72.27%	23.01%	4.51%	0.21%	-
	adults	0.072	0.11	93.97%	5.94%	0.08%	0.01%	-
Gomel City (inhabitants who lived in the city in April-May 1986)	children up to 18 y	0.19	0.38	67.70%	25.00%	6.34%	0.84%	0.12%
	adults	0.048	0.073	97.98%	1.96%	0.06%	-	-
Minsk City (inhabitants who lived in the city in April-May 1986)	children up to 18 y	0.038	0.083	94.07%	5.57%	0.36%	-	-
	adults	0.011	0.017	100.00%	-	-	-	-

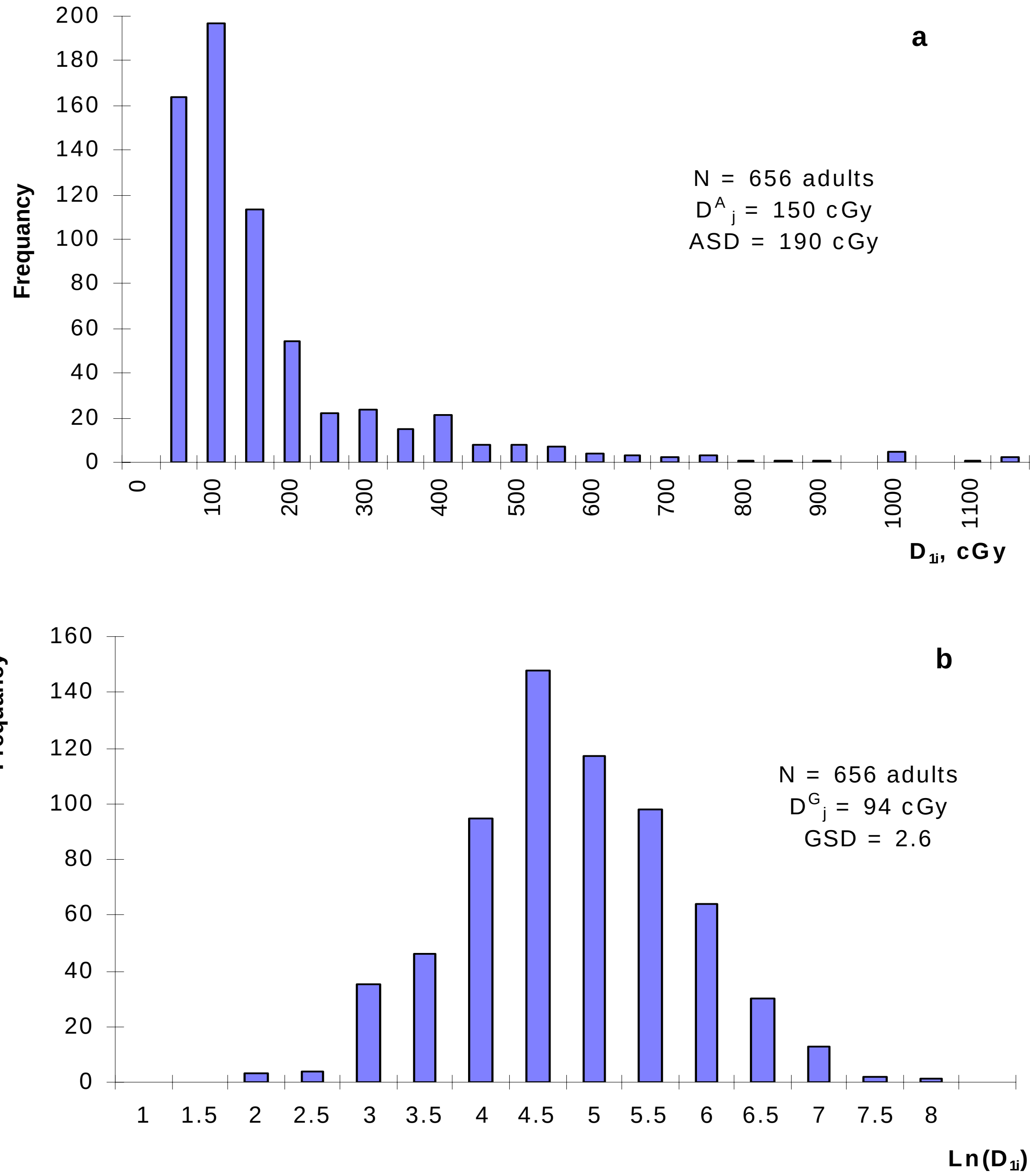


Fig.1 The distributions of individual thyroid dose estimates for the adult population in village Pogonnoe in Khoiniki raion in Gomel Oblast in two views: (a) - normal, and (b) - log-normal. There are: $D^A{}_j$ - arithmetic mean of individual dose estimates, ASD - arithmetic standard deviation, $D^G{}_j$ - geometric mean of individual dose estimates, GSD - geometric standard deviation.

The main sources of uncertainties attached to estimates of relative contribution of short-lived radioiodines to thyroid exposure are: (1) ratio between the internal thyroid doses from ingestion and inhalation intake of ^{131}I; (2) ratio between time-integrated activities of ^{132}Te and ^{131}I in ground-air and in ground-depositions.

Report on

The methodology used to calculate individual thyroid doses for the Belarusian people on the basis of available results of direct thyroid measurements

FENIX

Moscow

December 2000

INTRODUCTION

More than 200,000 measurements of exposure rate against the neck for the purpose of determining the thyroidal ^{131}I content, in vivo, were carried out for the Belarussian people in May-beginning of June 1986. However, the results of the measurements were affected by different factors: (1) the personnel of mobile teams, formed to monitor the thyroid glands of inhabitants, did not have adequate training to perform such measurements, with the exception of a few individuals; (2) because of the lack of special equipment simple survey meters with output in exposure or count rate were used; and (3) the procedure of thyroid measurements and their recording was not standardized. Such specific of the measurements substantially affected the results obtained. So it was necessary to reveal and quantitatively estimate all significant systematic and random sources of errors realized. Moreover there was no interviewing of measured people about their duration of residing in contaminated areas, fresh milk consumption etc., what is necessary to have for determining the dynamics of intake of ^{131}I to the individuals to estimate individual thyroid dose.

The purposes of this report are to (1) describe the methodology of assessment of individual thyroid doses on the basis of the results of direct thyroid measurements carried out for the Belarussian inhabitants, and (2) make a general presentation of the currently available results of individual thyroid doses.

THE METHODOLOGY OF THYROID DOSE ASSESSMENT FOR CHILDREN WITH IN-VIVO THYROID MEASUREMENTS

The formula of thyroid dose calculation (D) due to internal exposure from β-γ-rays of ^{131}I can be written as:

$$D = \frac{E_e}{m} \times F(t_m) \times G(t_m) \qquad (1)$$

where- N is the number of seconds in a day (= 86400 s d^{-1})

- E_e/m is the quotient of the average energy of β-γ radiation absorbed in the thyroid per radioactive decay of ^{131}I, in Joules, and of the mass of the thyroid, in kg; the numerical values of E_e/m are based on data proposed in ICRP Publication 56 (ICRP 1990). The values of E_e/m are in the range from 1.6×10^{-12} J kg^{-1} per radioactive decay of ^{131}I for the adult to 1.9×10^{-11} J kg^{-1} per radioactive decay of ^{131}I for the newborn;
- $G(t_m)$ is the ^{131}I content in the thyroid at the time of measurement t_m, Bq; and
- $F(t_m)$ is the function describing the kinetics of ^{131}I in the human thyroid, d.

Equation (1) stresses relative independence of the two tasks to be solved: (a) determination of the thyroidal ^{131}I content, $G(t_m)$, on the basis of the direct thyroid measurements; and (b) description of time dependence of ^{131}I intake, which determine the function $F(t_m)$.

Determination of the thyroidal ^{131}I content

The human thyroidal ^{131}I content $G(t_m)$ at the time of measurement t_m was calculated according to the formula (Gavrilin et al. 1999):

$$G(t_m) = k(d,j) \times [P_{th}(t_m,d)-P_b(t_m,d)] = k(d,j) \times P_J(t_m,d) \qquad (2)$$

where: $k(d,j)$ is a calibration coefficient relating the ^{131}I activity in the thyroid to the indication of the specific instrument, Bq h μR^{-1}; the value of $k(d,j)$ depends on the type of measuring device, d, and on the age, j, of the measured individual;

$P_{th}(t_m,d)$ is the indication of the instrument during the measurement near the thyroid, $\mu R\ h^{-1}$;

$P_b(t_m,d)$ is part of the indication of the instrument due to environmental radiation at the place of measurement, contaminated clothing, internal and external contamination of body, etc., (so called "background of the method"), $\mu R\ h^{-1}$;

$P_J(t_m,d)$ is part of the indication of the instrument due to thyroidal ^{131}I content, $\mu R\ h^{-1}$.

There is only one measured parameter in eqn (2) - $P_{th}(t_m,d)$. To calculate $G(t_m)$ it is necessary to estimate the values of: (1) a calibration coefficient, $k(d,j)$, and (2) background of the method, $P_b(t_m,d)$.

<u>Characteristics of the direct thyroid measurements:</u> The following survey meters were used in a large-scale monitoring of the Belarusian inhabitants: the DP-5, which has a Geiger-Muller counter as a detector (was used for about 80% of all measurements), the SRP-68-01 (~18%) and the DRG3-02 (~2%), which have NaI(Tl) scintillation detectors. All these devices have analog outputs with 95% confidence intervals of no better than 30% for the DP-5 instrument and 10% for the SRP-68-01 and the DRG3-02 instruments.

Because thyroid monitoring mainly started after May 5, 1986 (ten days after the accident) it can be considered that all short-lived radioiodines (^{132}I, ^{133}I, ^{134}I, and ^{135}I) had been decayed by the time of the measurements and only ^{131}I was in thyroids (Arefieva et al. 1988).

All the results of thyroid measurements can be divided into four groups of reliability depending upon the conditions of measurements (Table 1).

Table 1. Characteristics of reliability of the thyroid measurements used to assess individual thyroid doses in the available database for Belarusian people depending upon the conditions of measurements.

Group of reliability	Percentage of measurements	Devices	Locations	Comments
1	~4	DRG3-02, SRP-68-01	Hospitals in Minsk and Gomel Cities	Low background. Several measurements. Removal of clothes and wash themselves prior to the measurements
2	~19	SRP-68-01	Medical policlinics N28 and N5 in Minsk City	Low background. Single measurements of the Minsk inhabitants. Low level or absence of surface contamination.
3	~25	DP-5	Hospitals in Gomel and Mogilev Cities, centers of raions, sanatoria, rest houses, pioneer camps etc.	Low background. As a rule removal of clothes and wash themselves prior to the measurements
4	~52	DP-5	Directly at the places of residing	High background. Presence of surface contamination during measuring procedure

Assessment of the values of calibration coefficient: In order to obtain necessary actual information on the values of calibration coefficient k(d,j) for different types of instrument and different geometry of measurements (it was revealed that the measurements with the DP-5 instrument had been carried out under several operational conditions) we conducted in Moscow Clinics N6 in 1988-1989 special investigation for the adults (who consumed ^{131}I according to medical prescription). The results of that investigation are presented in Table 2. It is seen that under standard conditions of operation the least uncertainty of calibration coefficient k(d,ad) is attached to use of the SRP-68-01 instrument.

The values of parameter k(d,j) for children of age j are expressed through the corresponding values of that parameter for the adults in the following view:

$$k(d,j) = k(d,ad) \times l_j \quad (3)$$

where l_j is the relative age dependent coefficient, rel. unit.

The values of l_j coefficient for the “standard geometry” of thyroid measurement by the SRP-68-01 instrument, are presented in Table 3.

Table 2. The values of calibration coefficient k(d,j) for adults under standard# operational conditions (for all the instruments) and nonstandard$ operational conditions (only for the DP-5 instrument) of the measurements of thyroid.

Type of instrument	Operational conditions	Number of measur.	Characteristics of calibration coefficient k(d,j)		
			Geometric mean, expressed in terms:		GSD
			instrument scale	kBq h mR^{-1}	
SRP-68-01	Standard#	110	0.17 kBq h μR^{-1}	170	1.23
DRG3-02	Standard#	110	960 kBq s μR^{-1}	270	1.28
DP-5	Standard#	110	370 kBq h mR^{-1}	370	1.30
DP-5	Nonstandard$ (1)	78	670 kBq h mR^{-1}	670	1.20
DP-5	Nonstandard$ (2)	76	930 kBq h mR^{-1}	930	1.20
DP-5	Nonstandard$ (3)	73	310 kBq h mR^{-1}	310	1.29

Standard# - Detector of the instrument is placed against the neck under the thyroid. Under that detecting elements of the SRP-68-01 and DRG3-02 instruments are directed to thyroid with toroidal surface, and of the DP-5 instrument are directed to thyroid with sidelong surface with window closed by moving shield.

Nonstandard$ (1) - The detector is placed against the neck rotated with 180^0 relatively its cylindrical axis in comparison with its standard position.

Nonstandard$ (2) - Position of the detector is analogous to nonstandard (1) with additional shift from the neck as far as about 1.5 cm.

Nonstandard$ (3) - Position of the detector is standard, but the window is not closed with the moved shield.

Table 3. The values of l_j coefficient, calculated for the "standard geometry" of children's thyroid measurements by the SRP-68-01 instrument (Stepanenko, 1989).

Age	l_j, rel.unit
Newborn	0.60
1 y	0.63
5 y	0.68
10 y	0.80
15 y	0.89
Adult	1.0

The same values of l_j coefficient we used for the DP-5 and the DRG3-02 instruments.

Assessment of background of the method: The highest difficulties were arisen to estimate $P_J(t_m,d)$, because the instruments considered registered gross gamma irradiation from all the sources available while it was necessary to separate only that part of the indication of the instrument which was due to radiation of the thyroidal ^{131}I content. To separate that contribution it was necessary to subtract P_b, background of the method, from P_{th}, the indication of the instrument. Background of the method was due to three factors: (1) environmental radiation at the place of measurement, (2) external radioactive contamination of body surface and clothes, and (3) internal radioactive contamination besides ^{131}I activity in thyroid.

As a matter of fact, we used the three methods to assess background of the method, P_b:

1). If there were two measurements carried out for an individual: one against the thyroid and the other, to take account of the background, against the liver, than the latter measurement was considered to be an estimate of P_b.

2). If there was no measurement against the liver but the result of measurement in air in the absence of a subject was recorded, then the recorded result of measurement in air was accepted to be an estimate of P_b.

3). If there was neither measurement against the liver nor result of measurement in air in the absence of a subject, then the following procedure was used if that subject was measured with several tens of others at the same place by the same operator during a day. The value of the background exposure rate was estimated on the basis of the distribution of the values of exposure rate against thyroid obtained during the same day at the same location. The value of the background exposure rate for the individuals was taken to be equal to the arithmetic mean of the three lowest values of exposure rate against thyroid for that day at that location. We assume that at least a few people measured among several tens did not drink milk and washed themselves prior to the measurements.

Unfortunately, for the majority of the people measured in Belarus only results of exposure rate against thyroid were recorded.

In principle, the second and the third approach for assessment of background measurement in fact allows assessing only part of background measurements due to environmental radiation at the place of measurement. It means that for such people the background level was systematically underestimated.

In 1987-1990 when we conducted initial analysis of the thyroid measurements and interviewed the operators, who had conducted the measurement, we revealed that the DP-5 instrument was used under several conditions and it was in many cases not clear if it had been used in the correct conditions ("standard geometry" of thyroid measurement) or if the correct unit was reported. Also, it often happened that the subjects did not wash themselves and/or wore contaminated clothes. Such kind of measurements made by DP-5 resulted in additional errors in determination of the ^{131}I thyroidal content in comparison with the measurements made by the SRP-68-01 and the DRG3-02 in hospitals when the subjects had been washed themselves and contaminated clothes had been removed before the measurements were conducted.

In order to exclude systematic errors due to use of the DP-5 device we used the following procedures.

If among the subjects, measured by the DP-5 in a given measuring point during one day, there had been some persons who later were measured in hospitals by the SRP-68-01 and the DRG3-02 devices, than the value of additional coefficient (k_s) is determined to take into account the systematic errors (in determination of the ^{131}I thyroidal content) caused by the specific conditions of the DP-5 measurements.

$$k_s = \exp\{ \sum_{i=1}^{n} \frac{1}{n} \times \ln[G_i(t_{mS}) \times f(t_{mS}, t_{mD}) / G_i(t_{mD})] \} \quad (4)$$

where $G_i(t_{mS})$ is the ^{131}I thyroidal content estimate for i-th individual measured by the SRP-68-01 (DRG3-02) in hospitals at the time t_{mS}, Bq;

$G_i(t_{mD})$ is the ^{131}I thyroidal content estimate for i-th individual measured by the DP-5 in the measuring point considered at the time t_{mD}, Bq;

$f(t_{mS},t_{mD})$ is the function taking into account kinetics of ^{131}I intake during the time from t_{mD} to t_{mS}, rel. unit; and

n is total number of subjects measured in the measuring point considered and later in hospitals.

As a rule the values of function $f(t_{mS},t_{mD})$ were calculated assuming that there hadn`t been any iodine intake during the time from t_{mD} to t_{mS}.

Below are some of the examples of the values of coefficient k_s in equation (4), which were calculated for the subjects measured with the SRP-68-01 and the DP-5 instruments. The mean value of that coefficient for the 32 settlements of Gomel Oblast is equal to 1.5. At the same time for one settlement - Pogonnoe village (Khoiniki raion) the value of that coefficient for some sets of thyroid measurements was equal to 4.8 and for one settlement Zalesye village (Bragin raion) the value of k_s for some sets of thyroid measurements was equal to 3.5. The lowest value of k_s was equal to 0.6 for the measurements in Omelkovshina (Khoiniki raion). The values of k_s for the other places were in the range: from 1 to 3 for the population in Narovlya raion; about 1 - for Buda-Koshelev, Korma, Vetka, Rechitsa, and Loev raions; and from 1 to 1.5 - for 5 raions in Mogilev Oblast.

Another way to take into account systematic errors incorporated into results of measurements carried out by the DP-5 device is as follows. If there are several sets of measurements of the residents of a given settlement (a set of measurements is considered to be the results of measurements carried out by one operator at one location during one day) we choose the most reliable set of measurements (for example, where the SRP-68-01 was used) as a reference set. During that procedure we have as a guiding line the assessment of exposure rate near thyroid for a typical resident of a given settlement calculated for May 30 by use of the semiempirical model. We determined average exposure rate for each set of measurements (only if the number of measured persons in this set is more then 10) and after that calculated the received values to the same conditional date - May 30. If comparison of the average exposure rate P_j for a considered set of measurement "j" with the average exposure rate P_{ref} for a reference set of measurements shows the following ratio $P_{ref}/2 < P_j < 2 \times P_{ref}$ no corrections are used. Otherwise,

if $P_j > 2 \times P_{ref}$ correction factor $\mu = 2 \times P_{ref}/P_j$ is used;

if $P_j < P_{ref}/2$ correction factor $\mu = P_{ref}/P_j \times 2$ is used.

Use of correction coefficient implies that all the individual results of exposure rate (after subtraction of background) in set "j" are multiplied by μ. Again, if the number of the persons in the set considered was less then 10 measurements no corrections were incorporated.

Determination of the kinetics of ^{131}I intake

The dynamics of the radioiodine intake to the individuals can be determined on the basis of the information about their actual residence and consumption of foodstuffs in April-May 1986. In order to obtain such information we organized in 1988 personal interviewing of the evacuees and the residents of the controlled areas of Gomel and Mogilev Oblasts. About 150,000 people were interviewed. Interviewing was aimed at collecting the following personal information: (1) location of residing and the dates of residence from April 26 through May 31 1986, (2) duration of fresh milk consumption (if any) and the dates when the cows (goats) began to consume pasture grass, and (3) the dates when potassium-iodide pills were taken.

Basic concept: It was accepted that the rural residents consumed fresh milk locally produced (the most significant contributor to ^{131}I exposure to the thyroids). So individual thyroid dose was a linear function of the individual's milk-consumption rate. On the contrary, for the urban population we accepted that there was no a linear relationship between the level of the individual thyroid dose and the individual's milk-consumption rate. The assumption regarding urban residents was derived from the following circumstances. During April and May 1986 fresh milk was delivered to cities from various sources including dairy farms located in contaminated and noncontaminated areas. That resulted in high variation of radioiodine concentration in milk over different city shops and even within one shop over several consequent days. It means that a subject who consumed small amount of milk with high radioiodine concentration was exposed to higher dose than that who consumed large amount of milk with low radioiodine concentration.

Intake functions for rural residents: On the basis of joint analysis of collected results of personal interviewing and the information of peculiarities of radioactive fallout, typical models of ^{131}I intake to the Belarusian rural inhabitants were obtained and formulas to calculate $F(t_m)$ were derived for 11 variants of intake (Gavrilin et al. 1989) see in Appendix.

The model of single occurrence of fallout in the vicinity of the places of residence including the pasture territories has been accepted for all territories in Gomel and Mogilev Oblasts. Following are the dates of ^{131}I fallout for the areas where thyroid measurements were conducted (Makhon`ko et al. 1996):

- April 27, for inhabitants of southern and western raions in Gomel Oblast;
- April 28, for inhabitants of north-eastern raions in Gomel Oblast (including Gomel city), all the territory of Mogilev Oblast.

The information obtained as a result of personal interviewing related to each individual can be divided into four groups:

1) the dates of residents in each village from April 26, 1986 through May 31, 1986;
2) the date when cow (goat) was first put on pasture in his village in 1986;
3) the date when individual started taking potassium-iodide pills and time duration (days) of its taking;

4) the date when the consumption of fresh cow's milk of local origin was stopped.

Besides the above mentioned data, the information on the daily consumption rate of fresh milk was collected. But it is not necessary in the initial assessment of the direct thyroid doses, as long as it remained relatively constant during the time of exposure, so it was not used in thyroid dose calculation.

The analysis of the answers related to the first group revealed that as a rule the residents left their villages in May 1986 for less contaminated areas. That circumstance allowed us not to take into account all the residents from April 26 through May 31 for each individual, but only the first one and the corresponding date when individual was relocated or resettled (if appropriate).

For the last version of thyroid dose calculation, prepared by February 1996 (Khrouch et al.) we used the results of personal interviewing from the groups 1) and 2), which were estimated as relative reliable. For the time being we have not used the results of personal interviewing from the groups 3) and 4), for the quality of the answers is deemed to be relatively low.

Thus, if there is the information for an individual on the dates and locations where that subject was from April 26, 1986 through May 31, 1986, as well as the information on the date when cow (goat) was first put on pasture in his village in 1986. In case of absence such information the typical lifestyle and dietary habits for the residents in the settlement considered was accepted for description of radioiodine intake.

For example, the following typical lifestyle was revealed:

- interruption of milk consumption on May 3 by children and on May 4 by adults in evacuated (before May 5, 1986) villages in three south raions (Bragin, Khoiniki, and Narovlya) in Gomel Oblast;
- interruption of milk consumption on May 7 by children and on May 12 by adults in nonevacuated villages in three above mentioned raions;
- milk consumption was not interrupted in April through May 1986 by the residents in the other areas of Belarus.

Intake functions for urban residents: We developed the specific method to assess individual doses for the residents of Minsk city who lived in the city in April-May 1986. That method was derived directly from a large number of measurements available for the Minsk inhabitants from the beginning of May through the beginning of June 1986. Formula to calculate individual thyroid dose for such residents is as follows:

$$D = (F_g/f_{th}) \times G(t_m) \times k_{minsk} \times \exp(\lambda_{th} \times t_m/k_{minsk}) \quad (5)$$

where F_g is age-dependent dose coefficient for ingestion intake of ^{131}I, mGy Bq^{-1};

f_{th}=0.3 is the fraction of ingested radioiodine absorbed by the thyroid, dimensionless;

λ_{th} is the effective clearance rate of ^{131}I from the human thyroid, d^{-1}; its age-dependent values were derived from those proposed in ICRP Publication 56;

k_{minsk}=1.57 is empirically derived coefficient taking into account prolonged intake of ^{131}I, dimensionless.

Time of measurement, t_m, was counted from the day when the main fallout occurred. The values of F_g and λ_{th} used in thyroid dose calculations are presented in Table 4.

Table 4. The age-dependent values of the dose coefficient for ingestion intake of ^{131}I (F_g) and the effective clearance rate of ^{131}I from the human thyroid (λ_{th})

Age,	On the basis of the ICRP Publication 56	
y	F_g, 10^{-4} mGy Bq^{-1}	λ_{th}, d^{-1}
0-1	37.0	0.130
1-2	36.0	0.121
2-3	30.0	0.116
3-4	25.9	0.114
4-5	22.7	0.111
5-6	19.5	0.108
6-7	17.0	0.105
7-8	15.1	0.102
8-9	13.3	0.099
9-10	11.7	0.097
10-11	10.4	0.096
11-12	9.4	0.096
12-13	8.5	0.095
13-14	7.7	0.095
14-15	7.1	0.095
15-16	6.6	0.095
16-17	6.1	0.095
17-18	5.6	0.095
>18	4.4	0.094

For the residents with direct thyroid measurements who lived in other Belarusian cities (namely, Gomel, Mogilev, and Mozyr) in April-May 1986 another method was used. The dose for those residents was estimated as arithmetic mean of dose in case of only inhalation intake and of dose in case of only milk intake from family cow. That formula can be written as follows:

$$D = 0.5 \times \frac{F_g}{f_{th}} \times G(t_m) \times e^{\lambda_{th} \times t_m} \times \left(1 + \frac{(\frac{1}{\lambda_g} - \frac{1}{\lambda_c})}{\frac{1}{\lambda_g - \lambda_{th}} \times [1 - e^{-(\lambda_g - \lambda_{th}) \times t_m}] - \frac{1}{\lambda_c - \lambda_{th}} \times [1 - e^{-(\lambda_c - \lambda_{th}) \times t_m}]} \right) \quad (6)$$

where λ_g=0.15 d^{-1}, is the effective clearance rate of ^{131}I from pasture;

λ_c=0.627 d^{-1}, is the effective clearance rate of ^{131}I from cow to milk.

REFERENCES

Arefieva, Z.S.; Badyin, V.I.; Gavrilin, Yu.I.; Gordeev, K.I.; Ilyin, L.A.; Kruchkov, V.P.; Margulis, U.Ya.; Osanov, D.P.; Khrouch, V.T. Guidance on thyroid dose assessment for a man due to his radioiodine intake. Edited by Ilyin, L.A. Moscow: Energoatomizdat Publishing House; 1988 (in Russian).

Gavrilin, Yu.I.; Khrouch, V.T.; Shinkarev, S.M. Methodological principles of retrospective assessment of individual internal thyroid doses from radioiodine for Belarussian residents after the Chernobyl accident. Moscow; Institute of Biophysics Report No. B-5029; 1989 (in Russian).

Gavrilin, Yu.; Khrouch, V.; Shinkarev, S.; Krysenko, N.; Skryabin, A.; Bouville A.; Anspaugh L. Chernobyl accident: Reconstruction of thyroid dose for inhabitants of the Republic of Belarus. Health Phys. 76(2):105-119; 1999.

ICRP - International Commission on Radiological Protection. Age-dependent doses to members of the public from intake of radionuclides: Part 1. Ingestion dose coefficients. ICRP Publication 56; Ann. ICRP 20(2); 1990.

Khrouch, V. T., Gavrilin, Yu. I., Shinkarev, S. M. Correction of individual thyroid dose estimates (calculated earlier using the results of direct thyroid measurements) on the basis of the results of personal interviewing and using the semiempirical formula. Moscow: Institute of Biophysics; Report No. 15-20/95; 1996 (in Russian).

Makhon`ko, K.P., Kozlova, E.G., Volokitin, A.A. Dynamics of radioiodine accumulation on soil and reconstruction of doses from iodine exposure on the territory contaminated after the Chernobyl accident. -Radiation and Risk. No. 7: 140-191; 1996 (in Russian).

Stepanenko, V.F. Report on the results of estimation of the values of age-dependent calibration coefficient relating the ^{131}I activity in the thyroid to the indication of the measuring instrument SRP-68-01. Research Institute of Medical Radiology of Academy of Medical Science of the USSR, Obninsk, 1989 (in Russian).

Description of the method of thyroid dose assessment for 11 typical modes of radioiodines intake to the rural Belarussian residents

The formula of thyroid dose calculation D due to internal exposure from β-γ-rays of ^{131}I is written as follows:

$$D = k_1 \times (E_e/m_{th}) \times G(t_m) \times F(t_m)$$

where: $k_1=8.64\times10^4$ is a coefficient equal to the number of seconds in a day, s d^{-1};

E_e is the average energy of β-γ radiation absorbed in the thyroid due to one radioactive decay of ^{131}I, in Joules;

m_{th} is the mass of the thyroid, kg; its age-dependent values are presented in [1];

$G(t_m)$ is the ^{131}I content in the thyroid at the time of measurement t_m, Bq; and

$F(t_m)$ is the function describing the kinetics of ^{131}I in the human thyroid, d.

Eleven modes of typical radioiodine intake and the corresponding formulas to calculate $F(t_m)$ are placed below:

Fig.1A contains the following indications:

t_s is the date when the subject stopped consuming fresh milk of local origin;

t_b is the date when the subject started taking potassium-iodide pills;

$t_c = t_b + t_{KI} +1$ is the date when blockade of iodine thyroid uptake finished;

t_{KI} is the number of days the individual took potassium-iodide pills;

All the dates were counted from the day when cows were first put on a contaminated pasture. The following new parameters are used in equations (A.1)-(A.11):

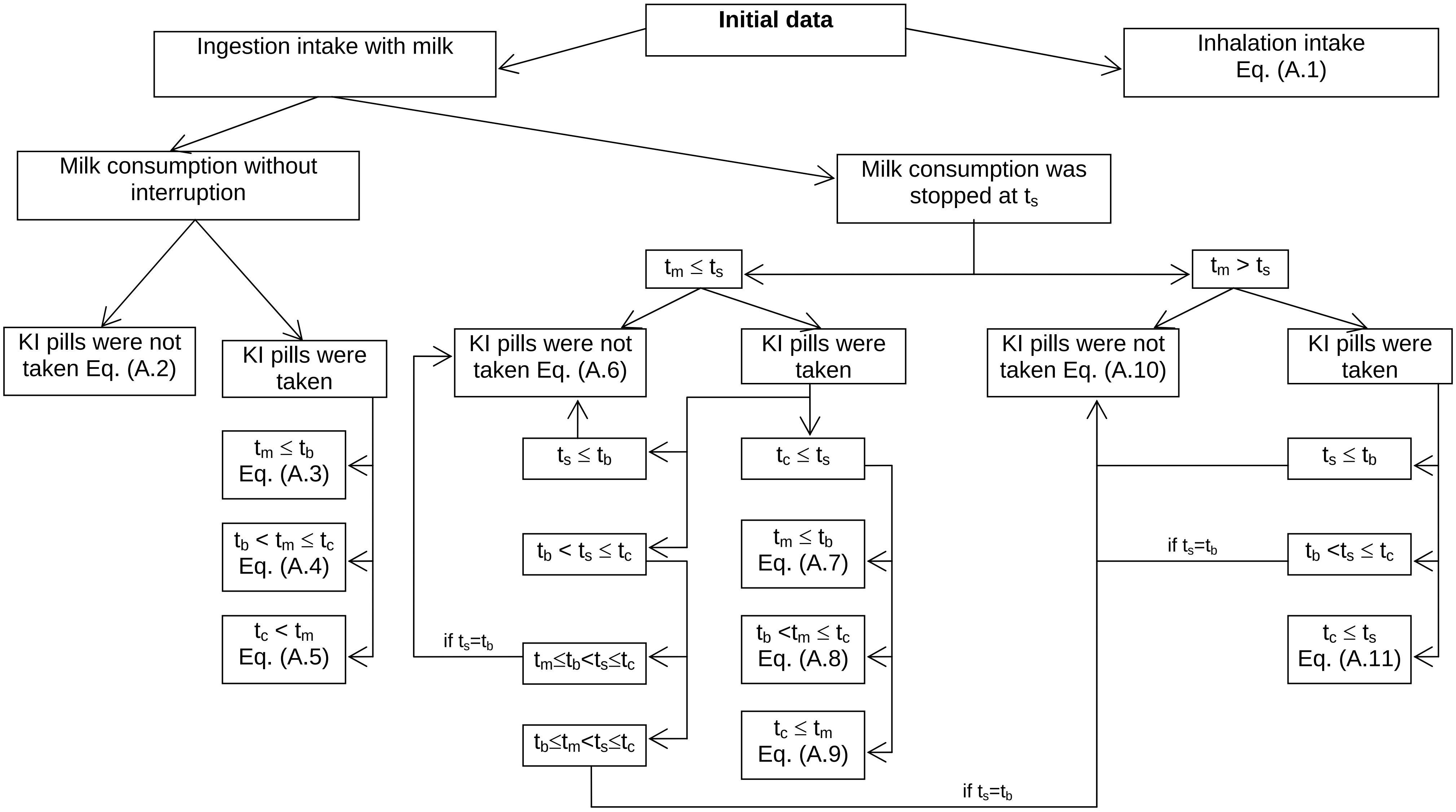


Fig.1A Algorithm of choosing an equation to calculate the values of $F(t_m)$ on the basis of direct thyroid measurements and the results of the 1988 interviewing.

The equations to calculate $F(t_m)$ (see Figure 1A)

$$F(t_m) = \frac{e^{\lambda_{th} \times t_m}}{\lambda_{th}} \tag{A.1}$$

$$F(t_m) = \frac{e^{\lambda_{th} \times t_m}}{\lambda_{th}} \times \frac{\left(\frac{1}{\lambda_c} - \frac{1}{\lambda_g}\right)}{\frac{1}{\lambda_c - \lambda_{th}} \times [1 - e^{-(\lambda_c - \lambda_{th}) \times t_m}] - \frac{1}{\lambda_g - \lambda_{th}} \times [1 - e^{-(\lambda_g - \lambda_{th}) \times t_m}]} \tag{A.2}$$

$$F(t_m) = \frac{e^{\lambda_{th} \times t_m}}{\lambda_{th}} \times \frac{\left[\frac{1}{\lambda_c} \times (1 - e^{-\lambda_c t_b} + e^{-\lambda_c t_c}) - \frac{1}{\lambda_g} \times (1 - e^{-\lambda_g t_b} + e^{-\lambda_g t_c})\right]}{\frac{1}{\lambda_c - \lambda_{th}} \times [1 - e^{-(\lambda_c - \lambda_{th}) \times t_m}] - \frac{1}{\lambda_g - \lambda_{th}} \times [1 - e^{-(\lambda_g - \lambda_{th}) \times t_m}]} \tag{A.3}$$

$$F(t_m) = \frac{e^{\lambda_{th} \times t_m}}{\lambda_{th}} \times \frac{\left[\frac{1}{\lambda_c} \times (1 - e^{-\lambda_c t_b} + e^{-\lambda_c t_c}) - \frac{1}{\lambda_g} \times (1 - e^{-\lambda_g t_b} + e^{-\lambda_g t_c})\right]}{\frac{1}{\lambda_c - \lambda_{th}} \times [1 - e^{-(\lambda_c - \lambda_{th}) \times t_b}] - \frac{1}{\lambda_g - \lambda_{th}} \times [1 - e^{-(\lambda_g - \lambda_{th}) \times t_b}]} \tag{A.4}$$

$$\begin{aligned} F(t_m) = {} & \frac{e^{\lambda_{th} \times t_m}}{\lambda_{th}} \times \left[\frac{1}{\lambda_c} \times (1 - e^{-\lambda_c \times t_b} + e^{-\lambda_c \times t_c}) - \frac{1}{\lambda_g} \times (1 - e^{-\lambda_g \times t_b} + e^{-\lambda_g \times t_c})\right] / \\ & / \left\{\frac{1}{\lambda_c - \lambda_{th}} \times [(1 - e^{-(\lambda_c - \lambda_{th}) \times t_b} + e^{-(\lambda_c - \lambda_{th}) \times t_c} - e^{-(\lambda_c - \lambda_{th}) \times t_m})] - \right. \\ & \left. - \frac{1}{\lambda_g - \lambda_{th}} \times [(1 - e^{-(\lambda_g - \lambda_{th}) \times t_b} + e^{-(\lambda_g - \lambda_{th}) \times t_c} - e^{-(\lambda_g - \lambda_{th}) \times t_m})]\right\} \end{aligned} \tag{A.5}$$

$$F(t_m) = \frac{e^{\lambda_{th} \times t_m}}{\lambda_{th}} \times \frac{\left[\frac{1}{\lambda_c} \times (1 - e^{-\lambda_c t_s}) - \frac{1}{\lambda_g} \times (1 - e^{-\lambda_g t_s})\right]}{\frac{1}{\lambda_c - \lambda_{th}} \times [1 - e^{-(\lambda_c - \lambda_{th}) \times t_m}] - \frac{1}{\lambda_g - \lambda_{th}} \times [1 - e^{-(\lambda_g - \lambda_{th}) \times t_m}]} \tag{A.6}$$

$$F(t_m)=\frac{e^{\lambda_{th}\times t_m}}{\lambda_{th}}\times\frac{\left[\frac{1}{\lambda_c}\times(1-e^{-\lambda_c t_b}+e^{-\lambda_c t_c}-e^{-\lambda_c t_s})-\frac{1}{\lambda_g}\times(1-e^{-\lambda_g t_b}+e^{-\lambda_g t_c}-e^{-\lambda_g t_s})\right]}{\frac{1}{\lambda_c-\lambda_{th}}\times[1-e^{-(\lambda_c-\lambda_{th})\times t_m}]-\frac{1}{\lambda_g-\lambda_{th}}\times[1-e^{-(\lambda_g-\lambda_{th})\times t_m}]} \quad (A.7)$$

$$F(t_m)=\frac{e^{\lambda_{th}\times t_m}}{\lambda_{th}}\times\frac{\left[\frac{1}{\lambda_c}\times(1-e^{-\lambda_c t_b}+e^{-\lambda_c t_c}-e^{-\lambda_c t_s})-\frac{1}{\lambda_g}\times(1-e^{-\lambda_g t_b}+e^{-\lambda_g t_c}-e^{-\lambda_g t_s})\right]}{\frac{1}{\lambda_c-\lambda_{th}}\times[1-e^{-(\lambda_c-\lambda_{th})\times t_b}]-\frac{1}{\lambda_g-\lambda_{th}}\times[1-e^{-(\lambda_g-\lambda_{th})\times t_b}]} \quad (A.8)$$

$$\begin{aligned}F(t_m)=&\frac{e^{\lambda_{th}\times t_m}}{\lambda_{th}}\times\left[\frac{1}{\lambda_c}\times(1-e^{-\lambda_c\times t_b}+e^{-\lambda_c\times t_c}-e^{-\lambda_c\times t_s})-\frac{1}{\lambda_g}\times(1-e^{-\lambda_g\times t_b}+e^{-\lambda_g\times t_c}-e^{-\lambda_g\times t_s})\right]/\\&/\left\{\frac{1}{\lambda_c-\lambda_{th}}\times[(1-e^{-(\lambda_c-\lambda_{th})\times t_b}+e^{-(\lambda_c-\lambda_{th})\times t_c}-e^{-(\lambda_c-\lambda_{th})\times t_m})]-\right.\\&\left.-\frac{1}{\lambda_g-\lambda_{th}}\times[(1-e^{-(\lambda_g-\lambda_{th})\times t_b}+e^{-(\lambda_g-\lambda_{th})\times t_c}-e^{-(\lambda_g-\lambda_{th})\times t_m})]\right\}\end{aligned} \quad (A.9)$$

$$F(t_m)=\frac{e^{\lambda_{th}\times t_m}}{\lambda_{th}}\times\frac{\left[\frac{1}{\lambda_c}\times(1-e^{-\lambda_c t_s})-\frac{1}{\lambda_g}\times(1-e^{-\lambda_g t_s})\right]}{\frac{1}{\lambda_c-\lambda_{th}}\times[1-e^{-(\lambda_c-\lambda_{th})\times t_s}]-\frac{1}{\lambda_g-\lambda_{th}}\times[1-e^{-(\lambda_g-\lambda_{th})\times t_s}]} \quad (A.10)$$

$$\begin{aligned}F(t_m)=&\frac{e^{\lambda_{th}\times t_m}}{\lambda_{th}}\times\left[\frac{1}{\lambda_c}\times(1-e^{-\lambda_c\times t_b}+e^{-\lambda_c\times t_c}-e^{-\lambda_c\times t_s})-\frac{1}{\lambda_g}\times(1-e^{-\lambda_g\times t_b}+e^{-\lambda_g\times t_c}-e^{-\lambda_g\times t_s})\right]/\\&/\left\{\frac{1}{\lambda_c-\lambda_{th}}\times[(1-e^{-(\lambda_c-\lambda_{th})\times t_b}+e^{-(\lambda_c-\lambda_{th})\times t_c}-e^{-(\lambda_c-\lambda_{th})\times t_s})]-\right.\\&\left.-\frac{1}{\lambda_g-\lambda_{th}}\times[(1-e^{-(\lambda_g-\lambda_{th})\times t_b}+e^{-(\lambda_g-\lambda_{th})\times t_c}-e^{-(\lambda_g-\lambda_{th})\times t_s})]\right\}\end{aligned} \quad (A.11)$$

__ANNEX 3__

SHORT DESCRIPTION OF THE APPLICATION OF THE SEMIEMPIRICAL MODEL TO ASSESS AVERAGE AGE-DEPENDENT THYROID DOSES IN THE SETTLEMENTS WHERE NO DIRECT THYROID MEASUREMENTS WERE CONDUCTED

Table 1a presents average age-dependent thyroid dose estimates calculated for all the Belarusian population living in six Oblasts. Separate estimates were done for two large cities (Minsk and Gomel), for which a representative number of the residents with "measured" thyroid doses is available [1]. Term "measured" thyroid dose indicates an individual thyroid dose calculated on the basis of the measurement of exposure rate against the neck (in order to determine thyroidal ^{131}I content at the time of measurement) conducted within a few weeks following the Chernobyl accident plus information on lifestyle and dietary habits of the individual considered. The average age-dependent thyroid doses for the children who lived in their cities in April-May 1986 were derived directly from the measured thyroid doses for representative samples of those children. The average age-dependent thyroid doses for the children in the six Oblasts were calculated using the semiempirical model, derived from the relationship obtained between the mean-adult-thyroid dose and the deposition density of ^{131}I and ^{137}Cs in villages for which a representative number of residents with direct thyroid doses was available.

Description of the method to calculate measured thyroid doses for the population of Belarus is presented in [1]. Extended description of some aspects of the semiempirical model is available in [1, 2]. Short presentation of the semiempirical model and the equations used in current estimation is given below.

In the framework of the semiempirical model the four equations to assess average thyroid dose for adult population, D_j, in a given rural settlement (j) were used depending upon the mode of deposition when fallout occurred in the vicinity of this settlement and available information on the mode of deposition:

(1) dry deposition only;

(2) wet deposition only;

(3) combined deposition (dry and wet) when it is possible to estimate value of dry deposition;

(4) combined deposition (dry and wet) when it is impossible to estimate value of dry deposition.

In case of dry deposition only (index – "dry")

$$D_j = C_{dry} \times R_{dry,j} \times q_{dry,j}, \ \text{Gy} \quad (1)$$

where $C_{dry} = 1.2 \times 10^{-7}$ Gy Bq^{-1} m^2 is empirically derived coefficient;

$R_{dry,j}$ is the average ratio of the ^{131}I-to-^{137}Cs ground-deposition density in the vicinity of settlement j under conditions of dry fallout, dimensionless;

$q_{dry,j}$ is average ground-deposition density of ^{137}Cs in the vicinity of settlement j due to dry deposition, Bq m^{-2}.

In case of wet deposition only (index – "wet")

$$D_j = C_{wet} \times R_{wet,j} \times q_{wet,j}, \ \text{Gy} \quad (2)$$

where $C_{wet} = 1.3 \times 10^{-8}$ Gy Bq^{-1} m^2 is empirically derived coefficient;

$q_{wet,j}$ is average ground-deposition density of ^{137}Cs in the vicinity of settlement j due to wet deposition, Bq m^{-2};

$R_{wet,j}$ is the average ratio of the ^{131}I-to-^{137}Cs ground-deposition density in the vicinity of settlement j under conditions of wet fallout, dimensionless.

In case of combined (dry and wet) deposition (index – "comb") when it is possible to estimate value of dry deposition in the vicinity of settlement (j):

$$D_j = C_{comb1} \times R_{dry,j} \times q_{dry,j} + B \times R_{comb,j} \times q_{comb,j}, \ \text{Gy} \quad (3)$$

where $C_{comb1} = 1.24 \times 10^{-7}$ Gy Bq^{-1} m^2 is empirically derived coefficient;

$R_{dry,j}$ is estimated average ratio of the ^{131}I-to-^{137}Cs ground-deposition density in the vicinity of settlement j under conditions of dry fallout, dimensionless;

$q_{dry,j}$ is estimated average value of ground-deposition density of ^{137}Cs in the vicinity of settlement j due to dry deposition, Bq m^{-2};

$B = 1.3 \times 10^{-8}$ Gy Bq^{-1} m^2 is empirically derived coefficient;

$R_{comb,j}$ is the average ratio of the ^{131}I-to-^{137}Cs ground-deposition density in the vicinity of settlement j under conditions of combined fallout, dimensionless;

$q_{comb,j}$ is average ground-deposition density of ^{137}Cs in the vicinity of settlement j due to combined deposition, Bq m^{-2}.

If estimation of value of dry deposition in the vicinity of settlement (j) is impossible to be done then it is necessary to delineate the territory (x) covering settlement (j) with combined fallout occurred from the same radioactive cloud with small variation of concentration of ^{131}I. The equation to assess D_j in such case is as follows:

$$D_j = C_{comb2} \times R_x \times q_x + B \times R_{comb,j} \times q_{comb,j}, \ \text{Gy} \quad (4)$$

where $C_{comb2} = 3.3 \times 10^{-8}$ Gy Bq^{-1} m^2 is empirically derived coefficient;

R_x is the average ratio of the ^{131}I-to-^{137}Cs ground-deposition density in territory (x) under conditions of combined fallout;

q_x is average ground-deposition density of ^{137}Cs over territory (x) with combined deposition, Bq m^{-2}.

In current assessment the procedure to delineate territories (x) was simplified and the administrative raions were selected as the territories (x). However, for the three raions: Bragin, Khoiniki, and Narovlya, located in the southern part of Gomel Oblast, additional differentiation was introduced between the areas inside and outside the 30-km zone around the Chernobyl Nuclear Power Plant.

Equations (1) through (4) were used to assess average thyroid dose for the adult populations in rural settlements, where cows had been first put on pasture before radioactive fallout occurred and residents consumed milk locally produced without any restrictions. For the territories where cows were first put on pasture after radioactive fallout had occurred and/or residents (1) were evacuated (relocated), (2) ceased milk consumption, (3) used iodine prophylaxis (4) etc. the corresponding multiply coefficients were applied to take into account those circumstances.

The data on ground-deposition density of ^{137}Cs in Belarusian settlements were taken from [3]. Only for a small part of the Belarusian settlements the estimates of the ratio of the ^{131}I-to-^{137}Cs ground-deposition density were derived from the results of spectrometric measurements conducted in May through July 1986. For the overwhelming majority of the settlements and areas of Belarus those ratios were assessed taking into account the pattern of the ratio of the ^{131}I-to-^{137}Cs in fallouts in Belarus.

Calculation of average age-dependent thyroid doses for children based on the dose estimates for adult population is as follows.

Because the main intake of ^{131}I was due to consumption of fresh milk locally produced the other pathways of ^{131}I intake (namely, inhalation and ingestion with leafy vegetables) are ignored. Typical representatives of children and adults are considered to have consumed milk after the accident.

Relationship between thyroid dose to an adult D(ad) and integrated activity of ^{131}I in milk consumed by an adult C(milk) can be written

$$D(ad) = Fg(ad) \times C(milk) \times Vmilk(ad) \times Kad(T) \qquad (5)$$

where

D(ad) is thyroid dose to an adult, Gy;

Fg(ad) is dose factor for ingestion intake by an adult, Gy Bq-1;

C(milk) is integrated concentration of 131I in milk, Bq L-1 d;

Vmilk(ad) is average milk consumption rate by an adult, L d-1;

Kad(T) is coefficient taking into account possible restriction period (T days) of milk consumption by an adult. In case no restriction was Kad(T)=1, dimensionless.

Relationship between thyroid dose to a child of a specific age D(ch) and integrated activity of ^{131}I in milk consumed by an adult C(milk) can be written

$$D(ch) = Fg(ch) \times C(milk) \times Vmilk(ch) \times Kch(T) \qquad (6)$$

where

D(ch) is thyroid dose to a child of a specific age, Gy;

Fg(ch) is dose factor for ingestion intake by a child of a specific age, Gy Bq-1;

C(milk) is integrated concentration of 131I in milk, Bq L-1 d;

Vmilk(ch) is average milk consumption rate by a child of a specific age, L d-1;

Kch(T) is coefficient taking into account possible restriction period (T days) of milk consumption by a child of a specific age. In case no restriction was Kch(T)=1, dimensionless.

Taking into account equations (5) and (6) and the fact that adults and children resided in the same village and drank the same milk one can write

$$D(ch) = D(ad) \times Fg(ch)/Fg(ad) \times Vmilk(ch)/Vmilk(ad) \times Kch(T)/Kad(T) \qquad (7)$$

Thus, equation (7) was used to calculate thyroid dose to a child of a specific age based on the thyroid dose to an adult. For those settlements where children and adults had the same duration of milk consumption the term Kch(T)/Kad(T)=1.

REFERENCES

1. Yu. Gavrilin, V. Khrouch, S. Shinkarev, N. Krysenko, A. Skryabin, A. Bouville, and L. Anspaugh, Chernobyl accident: Reconstruction of thyroid dose for inhabitants of the Republic of Belarus. *Health Phys.* **76**, 105–119 (1999).
2. Yu. I. Gavrilin, V. T. Khrouch and S. M. Shinkarev, Justification of the semiempirical model of internal thyroid doses formation and delineation of the territories (x) under assessment of mean-adult-thyroid dose for the rural population. *Bulletin of the Public Information Center on Atomic Energy* **11**, 33–41 (1999) (in Russian).
3. Hydrometeorological Committee of the Council of Ministers of the Republic of Belarus, *^{137}Cs Deposition Density at the Settlements of the Republic of Belarus at the Moment of January 1992.* Minsk, Report, 1992 (in Russian).

ANNEX 4

Thyroid Exposure of Belarusian and Ukrainian Children due to the Chernobyl Accident and Resulting Thyroid Cancer Risk

Report on

Re-evaluation of the estimates of age-dependent average doses for the residents of Gomel city

FENIX

GSF

November 2001

INTRODUCTION

The analysis of the dependency of thyroid dose estimates derived from direct thyroid measurements versus time of measurement carried out for the residents of Gomel city, who did not leave it for contaminated areas during the very first weeks following the Chernobyl accident, revealed obvious increase of thyroid dose estimates with time. At the fourth contractors meeting in Moscow held on June 25-27, 2001 GSF drew the participants´ attention to that fact. Also, it was written in the minutes of that meeting that "… for Gomel city such tendency could possibly be due to overestimation of the inhalation pathway contribution to the total thyroid dose. It was suggested to explore this problem in the future".

By the third contractors meeting held in Munich in December 2000, FENIX had presented the estimates of age-dependent average doses for more than 400 Belorussian settlements, including Gomel city, calculated from the individual thyroid doses assessed in 1996 on the basis of direct thyroid measurements. In July 2001 at Moscow meeting FENIX agreed that the problem related to the estimates of age-dependent average doses for the residents of Gomel city should be studied more carefully.

This report presents the analysis of the thyroid dose estimates for the residents of Gomel city and re-evaluation of the estimates of age-dependent average doses for those residents.

MATERIALS AND METHODS

Description of the direct thyroid measurements available for the residents of Gomel city

According to available information the measurements of ^{131}I thyroidal content for the residents of Gomel city were conducted at 50 different places of measurement. The number of citizens measured at those places was also very different and varied from 1 to 2499 people. The total number of the Gomel residents with direct thyroid measurements is 5613. We divided all the measured people into 5 groups taking into account the places and conditions of measurements. Those groups consisting of measured Gomel residents are as follows (Table 1):

Group 1 – 2499 people measured at Policlinics #28 of Minsk city;

Group 2 – 1723 people measured at Policlinics #1 of Gomel city;

Group 3 – 766 people measured at different hospitals of Minsk and Gomel cities;

Group 4 – 432 people measured at the Sankt-Petersburg Institute of Hygiene of Marine Vehicles;

Group 5 – 193 people measured at the other places of measurement.

Table 1. The division of all measured Gomel residents into five groups.

Group	Total		Adults		Children	
	persons	%	persons	%	persons	%
1	2499	44.5	1477	43.9	1022	45.4
2	1723	30.7	1285	38.2	438	19.5
3	766	13.7	391	11.6	375	16.7
4	432	7.7	107	3.2	325	14.5
5	193	3.4	104	3.1	89	3.9
Total	5613	100.0	3364	100.0	2249	100.0

Table 2 presents the distribution of all measured Gomel residents over dates of measurement and selected groups. Columns "persons with zero values" contain numbers of adults (children), for whom the level of exposure rate measured near thyroid was determined as undistinguished from the level of background exposure rate at the place of measurement.

Table 2. The distribution of all measured Gomel residents over dates of measurement and selected groups.

Date of measurement	**Group number**	**All measured population**	**Adults**		**Children**	
			Total number	**Persons with "zero values"**	**Total number**	**Persons with "zero values"**
1	**2**	**3**	**4**	**5**	**6**	**7**
01.05.86	Group 1	10	5	1	5	0
01.05.86	Group 5	1	1	0	0	0
02.05.86	Group 1	23	9	2	14	2
03.05.86	Group 1	7	6	0	1	0
03.05.86	Group 3	1	1	0	0	0
04.05.86	Group 1	16	12	7	4	0
04.05.86	Group 5	11	10	1	1	1
05.05.86	Group 1	85	53	4	32	3
05.05.86	Group 2	2	2	0	0	0
05.05.86	Group 3	1	0	0	1	0
05.05.86	Group 5	2	1	0	1	0
06.05.86	Group 1	194	131	4	63	4
06.05.86	Group 3	1	0	0	1	0
06.05.86	Group 5	2	1	0	1	0
07.05.86	Group 1	295	212	141	83	28
07.05.86	Group 3	5	0	0	5	0
07.05.86	Group 5	10	7	0	3	0
08.05.86	Group 1	197	140	88	57	20
08.05.86	Group 3	32	15	0	17	0
08.05.86	Group 5	20	3	0	17	8
09.05.86	Group 1	74	33	5	41	15
09.05.86	Group 3	66	30	0	36	2
10.05.86	Group 1	108	59	2	49	0
10.05.86	Group 3	45	18	0	27	0
10.05.86	Group 4	14	6	0	8	0
10.05.86	Group 5	3	3	2	0	0
11.05.86	Group 1	84	56	3	28	6

1	2	3	4	5	6	7
11.05.86	Group 3	97	71	7	26	1
11.05.86	Group 5	29	14	0	15	1
12.05.86	Group 1	170	98	35	72	9
12.05.86	Group 3	20	5	0	15	0
12.05.86	Group 4	8	2	0	6	0
12.05.86	Group 5	7	2	0	5	0
13.05.86	Group 1	107	45	3	62	13
13.05.86	Group 3	45	25	0	20	0
13.05.86	Group 4	16	1	0	15	0
13.05.86	Group 5	1	1	0	0	0
14.05.86	Group 1	164	102	7	62	4
14.05.86	Group 3	26	13	0	13	0
14.05.86	Group 4	12	0	0	12	0
14.05.86	Group 5	7	4	1	3	0
15.05.86	Group 1	72	21	2	51	1
15.05.86	Group 3	61	32	0	29	0
15.05.86	Group 4	18	9	0	9	0
15.05.86	Group 5	4	3	1	1	0
16.05.86	Group 1	73	34	3	39	3
16.05.86	Group 3	123	70	0	53	0
16.05.86	Group 4	29	8	1	21	1
16.05.86	Group 5	7	5	3	2	0
17.05.86	Group 1	130	79	18	51	2
17.05.86	Group 3	27	14	0	13	0
17.05.86	Group 4	23	8	0	15	0
17.05.86	Group 5	12	7	1	5	1
18.05.86	Group 1	69	36	1	33	1
18.05.86	Group 3	9	1	0	8	0
18.05.86	Group 4	5	2	0	3	0
18.05.86	Group 5	1	1	0	0	0
19.05.86	Group 1	81	47	0	34	0
19.05.86	Group 2	852	621	2	231	0
19.05.86	Group 3	67	37	0	30	0
19.05.86	Group 4	6	0	0	6	0
19.05.86	Group 5	7	5	0	2	1
20.05.86	Group 1	53	32	5	21	5
20.05.86	Group 2	391	304	1	87	0
20.05.86	Group 3	40	19	0	21	0
20.05.86	Group 4	17	1	0	16	0
20.05.86	Group 5	16	9	2	7	3
21.05.86	Group 1	65	38	3	27	1
21.05.86	Group 3	62	22	1	40	0
21.05.86	Group 4	21	4	0	17	0
21.05.86	Group 5	3	1	0	2	0
22.05.86	Group 1	125	56	21	69	4
22.05.86	Group 3	5	1	0	4	0
22.05.86	Group 4	14	5	0	9	0
22.05.86	Group 5	5	5	3	0	0
23.05.86	Group 1	8	8	1	0	0
23.05.86	Group 3	5	4	0	1	0
23.05.86	Group 4	15	2	0	13	0
23.05.86	Group 5	7	6	3	1	0
24.05.86	Group 1	43	29	5	14	0
24.05.86	Group 4	4	0	0	4	0
25.05.86	Group 1	16	7	0	9	1
25.05.86	Group 2	471	352	22	119	3
25.05.86	Group 3	3	2	0	1	0

1	2	3	4	5	6	7
25.05.86	Group 4	3	0	0	3	0
26.05.86	Group 1	47	31	10	16	0
26.05.86	Group 3	14	7	0	7	0
26.05.86	Group 4	22	5	0	17	0
26.05.86	Group 5	8	4	2	4	2
27.05.86	Group 1	47	23	0	24	2
27.05.86	Group 2	7	6	0	1	0
27.05.86	Group 3	3	3	0	0	0
27.05.86	Group 4	18	5	0	13	0
27.05.86	Group 5	2	2	0	0	0
28.05.86	Group 1	55	32	3	23	3
28.05.86	Group 3	4	0	0	4	0
28.05.86	Group 4	27	9	0	18	0
28.05.86	Group 5	2	1	0	1	0
29.05.86	Group 1	35	19	2	16	1
29.05.86	Group 3	1	0	0	1	0
29.05.86	Group 4	10	3	0	7	0
29.05.86	Group 5	1	1	0	0	0
30.05.86	Group 1	28	16	0	12	2
30.05.86	Group 4	13	5	0	8	0
31.05.86	Group 1	17	8	0	9	0
31.05.86	Group 4	6	2	0	4	0
31.05.86	Group 5	16	4	2	12	9
01.06.86	Group 1	1	0	0	1	0
01.06.86	Group 4	4	0	0	4	0
02.06.86	Group 3	1	0	0	1	0
02.06.86	Group 4	16	3	0	13	0
02.06.86	Group 5	9	3	1	6	0
03.06.86	Group 3	1	0	0	1	0
03.06.86	Group 4	10	2	0	8	0
04.06.86	Group 3	1	1	0	0	0
04.06.86	Group 4	8	1	0	7	1
05.06.86	Group 4	12	3	0	9	0
06.06.86	Group 4	5	1	0	4	0
07.06.86	Group 4	12	3	0	9	0
09.06.86	Group 4	13	3	0	10	0
10.06.86	Group 4	4	0	0	4	0
11.06.86	Group 4	13	3	0	10	0
12.06.86	Group 4	9	2	0	7	0
13.06.86	Group 4	4	1	0	3	0
16.06.86	Group 4	2	0	0	2	0
17.06.86	Group 4	9	0	0	9	0
19.06.86	Group 4	2	0	0	2	0
25.06.86	Group 4	5	5	0	0	0
26.06.86	Group 4	2	2	0	0	0
28.06.86	Group 4	1	1	0	0	0
Total		**5613**	**3364**	**432**	**2249**	**164**

Variation with time of integrated activity of ^{131}I in thyroid averaged for the Gomel residents of all ages (and for adult residents) for each of Groups at each date of measurement are presented in Table 3 (and Table 4), respectively. Only those average estimates were taken into account for which number of measurements was greater than 10.

Table 3. Variation with time of integrated activity of ^{131}I in thyroid averaged for the Gomel residents of all ages for each of five Groups at each date of measurement.

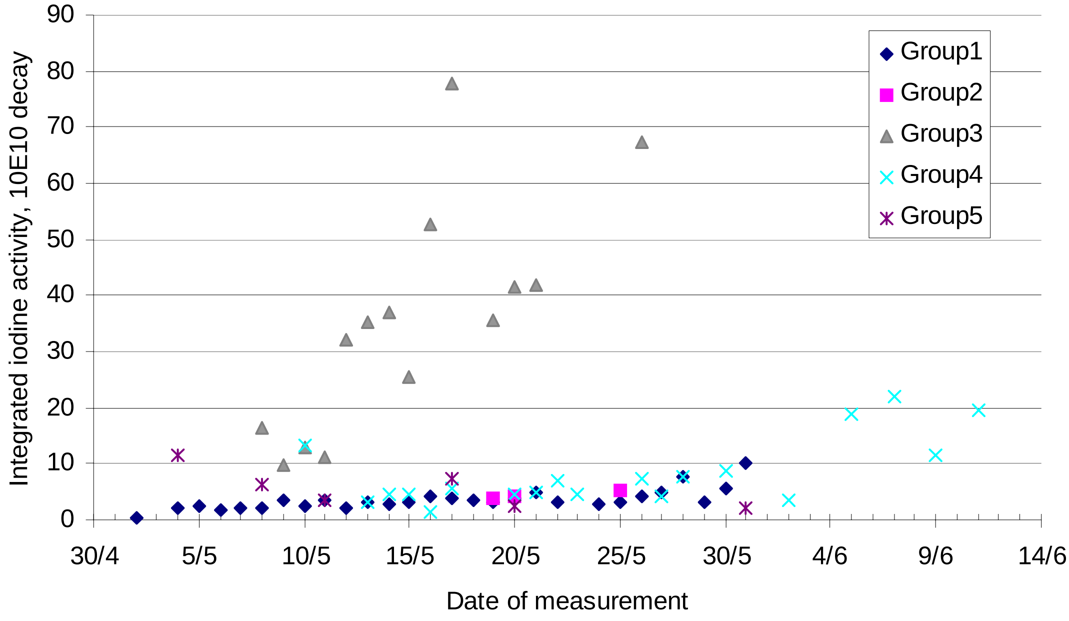
Date of measurement	Group1		Group2		Group3		Group4		Group5	
	#	Integrated activity of ^{131}I, 10^{10} decay	#	Integrated activity of ^{131}I, 10^{10} decay	#	Integrated activity of ^{131}I, 10^{10} decay	#	Integrated activity of ^{131}I, 10^{10} decay	#	Integrated activity of ^{131}I, 10^{10} decay
2.5	23	0.2								
4.5	16	2.0							11	11.4
5.5	85	2.4								
6.5	194	1.6								
7.5	295	2.0								
8.5	197	2.2			32	16.3			20	6.2
9.5	74	3.4			66	9.8				
10.5	108	2.4			45	12.8	14	13.1		
11.5	84	3.6			97	11.0			29	3.6
12.5	170	2.2			20	32.3				
13.5	107	3.2			45	35.3	16	3.0		
14.5	164	2.7			26	36.8	12	4.5		
15.5	72	3.0			61	25.6	18	4.6		
16.5	73	4.2			123	52.5	29	1.5		
17.5	130	3.8			27	77.9	23	5.5	12	7.4
18.5	69	3.4								
19.5	81	3.2	852	3.8	67	35.5				
20.5	53	4.0	391	4.2	40	41.6	17	4.5	16	2.3
21.5	65	4.8			62	42.0	21	5.0		
22.5	125	3.3					14	7.1		
23.5							15	4.6		
24.5	43	2.7								
25.5	16	3.0	471	5.1						
26.5	47	4.2			14	67.4	22	7.2		
27.5	47	4.8					18	4.0		
28.5	55	7.7					27	7.6		
29.5	35	3.1								
30.5	28	5.5					13	8.7		
31.5	17	10.3							16	1.9
1.6										
2.6							16	3.5		
3.6										
4.6										
5.6							12	18.9		
6.6										
7.6							12	22.0		
8.6										
9.6							13	11.6		
10.6										
11.6							13	19.5		

Table 4. Variation with time of integrated activity of ^{131}I in thyroid averaged for adult Gomel residents for each of five Groups at each date of measurement.

Date of measurement	Group1		Group2		Group3		Group5	
	#	Integrated activity of ^{131}I, 10^{10} decay	#	Integrated activity of ^{131}I, 10^{10} decay	#	Integrated activity of ^{131}I, 10^{10} decay	#	Integrated activity of ^{131}I, 10^{10} decay
4.5	12	2.3						
5.5	53	2.0						
6.5	131	1.7						
7.5	212	1.6						
8.5	140	2.0			15	19.0		
9.5	33	5.3			30	10.9		
10.5	59	3.4			18	9.4		
11.5	56	2.6			71	11.7	14	4.5
12.5	98	2.4						
13.5	45	3.9			25	38.7		
14.5	102	2.7			13	34.1		
15.5	21	3.4			32	33.3		
16.5	34	6.1			70	64.3		
17.5	79	3.6			14	89.6		
18.5	36	3.9						
19.5	47	3.1	621	3.6	37	45.2		
20.5	32	4.2	304	4.2	19	43.5		
21.5	38	5.0			22	57.7		
22.5	56	2.5						
23.5								
24.5	29	3.0						
25.5			352	4.5				
26.5	31	3.9						
27.5	23	6.5						
28.5	32	10.6						
29.5	19	3.9						
30.5	16	6.8						

On the basis of analysis of places and conditions of measurement we decided that the people included into Groups 1 and 2 are likely to be the representative for those Gomel residents who did not leave the city during the very first weeks after the accident. It is interesting to note that this solution was made regardless of comparison of average doses received by people in different groups. Performance of such comparison (see Figures 1 and 2) shows us that the Gomel people included into Groups 3 through 5 have received higher doses comparing to the doses for people included into Groups 1 and 2. It can be explained that the people from Groups 3 through 5 (or substantial part of such people) might have left the city for contaminated areas in Gomel Oblast during a few weeks following the accident. Thus, the data presented in Tables 3 and 4 and in Figures 1 and 2 confirm our above mentioned solution. It is also clearly seen that the curves related to Groups 1 and 2 in Figures 1 and 2 show the same tendency - "the later measurements were conducted the higher average integrated activity was estimated".

(a)



(b)

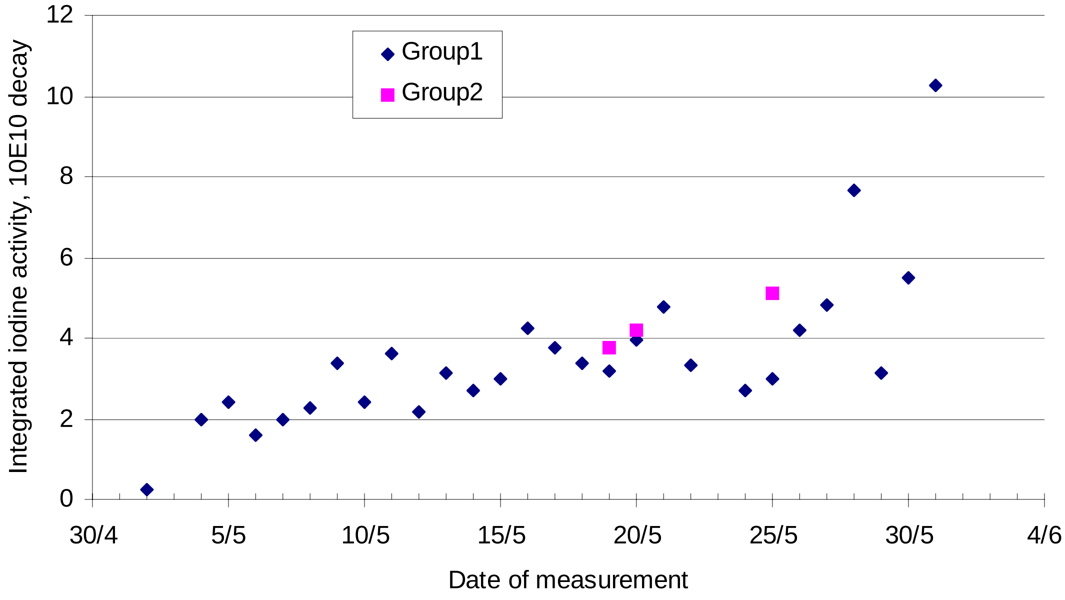
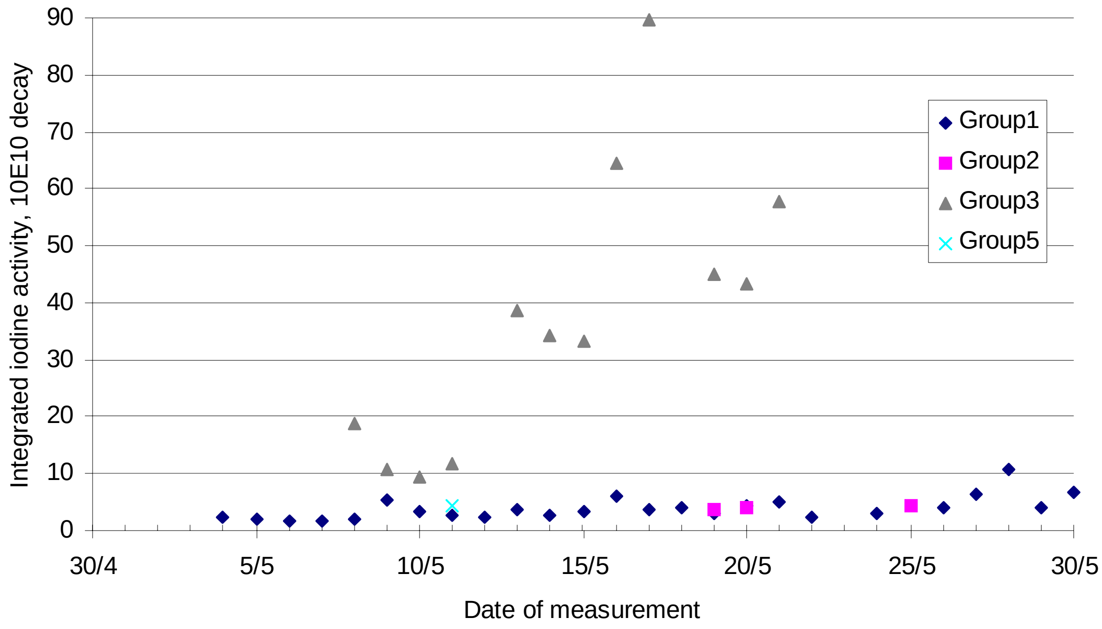


Fig.1. Variation with time of integrated activity of ^{131}I in thyroid averaged for the Gomel residents of all ages for each of the five Groups at each date of measurement.

(a) - Groups 1 through 5;

(b) - Groups 1 and 2.

(a)



(b)

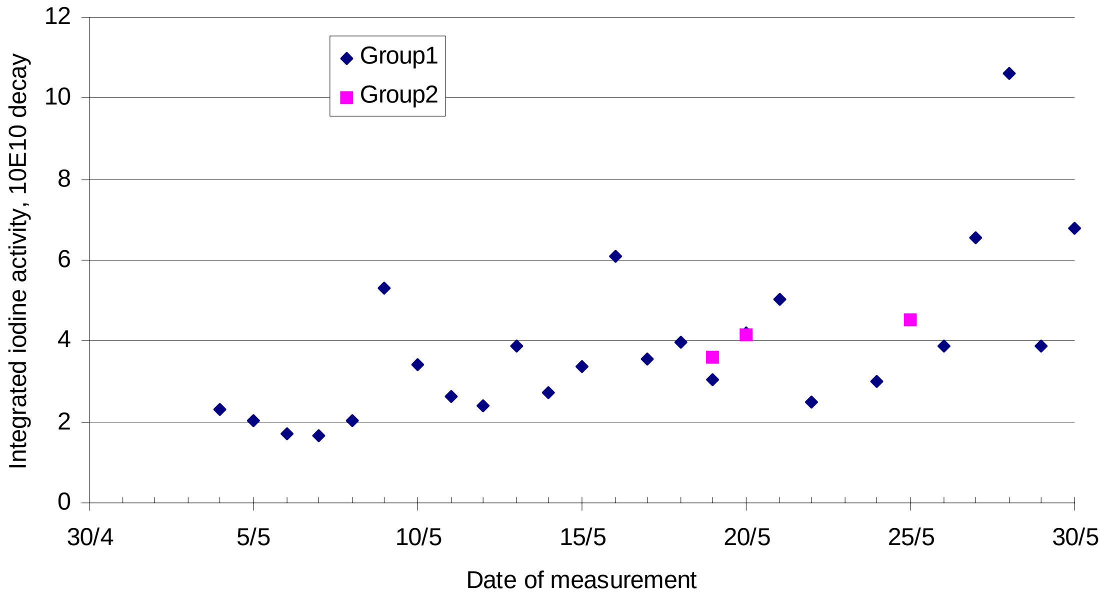


Fig.2. Variation with time of integrated activity of ^{131}I in thyroid averaged for adult Gomel residents for each of the five Groups at each date of measurement.

(a) - Groups 1 through 5;

(b) - Groups 1 and 2.

Methods of thyroid dose assessment for the residents of Gomel city on the basis of direct thyroid measurements

The general formula of thyroid dose calculation, D_m, due to internal exposure from β-γ-rays of ^{131}I on the basis of direct thyroid measurements is as follows:

$$D_m = k_1 \times (E_e/m_{th}) \times G(t_m) \times F(t_m) \quad (1)$$

where: $k_1=8.64\times10^4$ is a coefficient equal to the number of seconds in a day, s d^{-1};

E_e is the average energy of β-γ radiation absorbed in the thyroid due to one radioactive decay of ^{131}I, in Joules;

m_{th} is age-dependent mass of the thyroid, varies from 1.4 g for the newborn to 20 g for the adult; kg;

$G(t_m)$ is the ^{131}I content in the thyroid at the time of measurement t_m, Bq;

$F(t_m)$ is the function describing the kinetics of ^{131}I in the human thyroid, d.

The ^{131}I thyroidal content, $G(t_m)$, at the time of measurement, t_m, was calculated according to the formula:

$$G(t_m) = k_{ad} \times k_{ch} \times [P_{th}(t_m)-P_b(t_m)] \quad (2)$$

where: k_{ad} is a calibration coefficient relating the ^{131}I activity in adult thyroid to the indication of the measuring instrument, Bq h μR^{-1}; the value of k_{ad} depends on the type of measuring device;

k_{ch} is a coefficient taking into account a difference between size of the thyroid and thickness of overlying tissue for adults and children; the value of that coefficient increases with age and was calculated to be equal to 0.6 for a newborn, and to 0.8 for a 10-y child;

$P_{th}(t_m)$ is the reading of the instrument during the measurement near the thyroid, $\mu R\ h^{-1}$;

$P_b(t_m)$ is the contribution to the reading due to environmental radiation at the place of measurement, contaminated clothing, internal and external contamination of body, etc., (called “background of the method”), $\mu R\ h^{-1}$.

For the Gomel residents who stayed in the city and did not leave it during the very first weeks following the accident it was assumed that half of individual thyroid dose was due to inhalation and the other half was due to ingestion (milk intake). However, the formula that was used to describe the kinetics of ^{131}I in the human thyroid, $F(t_m)$, did not follow the assumption accepted. The formula used to assess $F(t_m)$ was as follows:

$$F(t_m) = (F(t_m)_{inhal}+F(t_m)_{milk}) / 2 \qquad (3)$$

where: $F(t_m)_{inhal}$ is the function describing the kinetics of ^{131}I in the human thyroid in case of inhalation, d;

$F(t_m)_{milk}$ is the function describing the kinetics of ^{131}I in the human thyroid in case of milk intake, d;

$$F(t_m)_{inhal} = \frac{e^{\lambda_{th} \times t_m}}{\lambda_{th}} \qquad (4)$$

$$F(t_m)_{milk} = \frac{e^{\lambda_{th} \times t_m}}{\lambda_{th}} \times C_1 \qquad (5)$$

where $$C_1 = \frac{\left(\frac{1}{\lambda_g} - \frac{1}{\lambda_c}\right)}{\frac{1}{\lambda_g - \lambda_{th}} \times [1 - e^{-(\lambda_g - \lambda_{th}) \times t_m}] - \frac{1}{\lambda_c - \lambda_{th}} \times [1 - e^{-(\lambda_c - \lambda_{th}) \times t_m}]} \qquad (6)$$

λ_{th} is age-dependent effective clearance rate of ^{131}I from the human thyroid, d^{-1};

λ_g=0.15 d^{-1} is the effective clearance rate of ^{131}I from pasture;

λ_c=0.63 d^{-1} is the effective clearance rate of ^{131}I from cow to milk.

As a matter of fact formula (3) used to assess the function $F(t_m)$ distorted the assumption accepted for the Gomel residents and it underestimated individual thyroid dose for the Gomel residents measured at the beginning of May and overestimated individual thyroid dose for those residents who were measured at the end of May.

In order to derive the formula to estimate function $F(t_m)$ according to accepted assumption (50% of individual thyroid dose was due to inhalation and the other 50% was due to milk intake) we can write the following equations:

$$D_{inhal} = D_{milk} \qquad (7)$$

$$\text{or} \quad G_{inhal}(t_m) = G_{milk}(t_m) \times C_1 \qquad (8)$$

where $G_{inhal}(t_m)$ is part of ^{131}I thyroidal content at the time of measurement due to inhalation intake, Bq;

$G_{milk}(t_m)$ is part of ^{131}I thyroidal content at the time of measurement due to milk intake, Bq;

Certainly, ratio between $G_{inhal}(t_m)$ and $G_{milk}(t_m)$ varies with time. Besides, we have

$$G(t_m) = G_{inhal}(t_m) + G_{milk}(t_m) \qquad (9)$$

Using eqn (8) and eqn (9), we can write:

$$G_{inhal}(t_m) = G(t_m) \times C_1/(1+C_1) \qquad (10)$$

Taking into account eqns (4), (7), and (10) we get the following formula to assess $F(t_m)$

$$F(t_m) = 2 \times \frac{e^{\lambda_{th} \times t_m}}{\lambda_{th}} \times \frac{C_1}{1+C_1} \qquad (11)$$

Thus, to assess individual thyroid doses for the Gomel residents according to accepted assumption we should have used eqn (11) rather than eqn (3) for assessment function $F(t_m)$ in general formula (1).

However, one can accept another assumption besides the above mentioned. The analysis of variation with time of ^{131}I thyroidal content for adult residents in Minsk city derived from direct thyroid measurements showed that it was similar to that as if the main pathway for the Minsk residents had been radioiodine intake with milk. So, let us consider another assumption regarding iodine intake for the Gomel residents, i.e. radioiodine intake with milk. In that case function $F(t_m)$ is calculated according to eqn (5).

So we have three variants of individual thyroid dose calculations. Each variant is associated with different equations to calculate function $F(t_m)$. Those three variants are as follows:

Variant 1 – function $F(t_m)$ is calculated according to eqn (3);

Variant 2 – function $F(t_m)$ is calculated according to eqn (11);

Variant 3 – function $F(t_m)$ is calculated according to eqn (5).

It is necessary to note that at the third collaborators meeting in Munich in December 2000 FENIX presented the estimates of age-dependent average doses for the Gomel residents calculated according to variant 1 of individual thyroid dose assessment.

RESULTS AND DISCUSSION

Presentation in section "Description of the direct thyroid measurements available for the residents of Gomel city" of all the data available for the measured Gomel residents divided into the five groups showed us that the data included into Groups 1 and 2 can be considered as the representative data for the Gomel residents who did not leave their city for the contaminated areas during the very first weeks following the accident. So for the further analysis we will merge Groups 1 and 2 into one Group and provide three sets of individual integrated activity of ^{131}I in thyroid for all the people in that merged Group according to the three variants of thyroid dose calculation considered in section "Methods of thyroid dose assessment for the residents of Gomel city on the basis of direct thyroid measurements".

Tables 5 and 6 present variation with time of integrated activity of ^{131}I in thyroid, IA, averaged for the residents of all ages and for the adult residents only, respectively, for each of three variants of individual thyroid dose calculation. Besides, the estimates of standard error of IA, integrated activity of ^{131}I in thyroid, are presented in those Tables. Similar to Tables 3 and 4 only those average estimates were taken into account for which number of measurements was greater than 10.

Table 5 Variation with time of integrated activity of ^{131}I in thyroid, IA, averaged for the Gomel residents of all ages for each of the three variants of individual thyroid dose calculation.

Date of measurement	#	Variant 1		Variant 2		Variant 3	
		Integrated activity of ^{131}I, IA, 10^{10} decay	Standard error of IA, 10^{10} decay	Integrated activity of ^{131}I, IA, 10^{10} decay	Standard error of IA, 10^{10} decay	Integrated activity of ^{131}I, IA, 10^{10} decay	Standard error of IA, 10^{10} decay
2.5	23	0.2	0.04	0.2	0.04	0.3	0.06
4.5	16	2.0	0.92	1.9	0.89	2.4	1.1
5.5	87	2.4	0.42	2.4	0.42	2.7	0.48
6.5	194	1.6	0.16	1.6	0.16	1.7	0.17
7.5	295	2.0	0.23	2.0	0.23	2.0	0.23
8.5	197	2.2	0.35	2.3	0.36	2.1	0.33
9.5	74	3.4	0.48	3.4	0.49	3.0	0.44
10.5	108	2.4	0.32	2.4	0.32	2.1	0.27
11.5	84	3.6	0.74	3.6	0.72	3.0	0.59
12.5	170	2.2	0.27	2.1	0.26	1.7	0.21
13.5	107	3.2	0.42	3.0	0.40	2.4	0.32
14.5	164	2.7	0.28	2.5	0.27	2.0	0.21
15.5	72	3.0	0.56	2.8	0.53	2.1	0.41
16.5	73	4.2	0.78	3.9	0.72	3.0	0.55
17.5	130	3.8	0.60	3.4	0.54	2.6	0.40
18.5	69	3.4	0.59	3.0	0.53	2.2	0.40
19.5	933	3.7	0.13	3.3	0.12	2.5	0.09
20.5	444	4.1	0.22	3.7	0.20	2.7	0.14
21.5	65	4.8	0.63	4.1	0.53	2.9	0.38
22.5	125	3.3	0.40	2.8	0.34	2.0	0.24
24.5	43	2.7	0.35	2.3	0.30	1.6	0.22
25.5	487	5.0	0.33	4.2	0.27	3.0	0.19
26.5	47	4.2	0.53	3.5	0.43	2.4	0.30
27.5	54	4.7	0.76	3.8	0.63	2.7	0.44
28.5	55	7.7	2.7	6.3	2.3	4.4	1.6
29.5	35	3.1	0.62	2.5	0.51	1.7	0.35
30.5	28	5.5	1.4	4.3	1.15	3.0	0.79
31.5	17	10.3	5.1	8.1	4.0	5.5	2.8

Table 6. Variation with time of integrated activity of ^{131}I in thyroid, IA, averaged for the adult Gomel residents for each of the three variants of individual thyroid dose calculation.

Date of measurement	#	Variant 1		Variant 2		Variant 3	
		Integrated activity of ^{131}I, IA, 10^{10} decay	Standard error of IA, 10^{10} decay	Integrated activity of ^{131}I, IA, 10^{10} decay	Standard error of IA, 10^{10} decay	Integrated activity of ^{131}I, IA, 10^{10} decay	Standard error of IA, 10^{10} decay
4.5	12	2.3	1.2	2.3	1.2	2.8	1.5
5.5	55	2.0	0.48	2.0	0.48	2.3	0.55
6.5	131	1.7	0.20	1.8	0.20	1.9	0.21
7.5	212	1.6	0.22	1.7	0.23	1.7	0.22
8.5	140	2.0	0.36	2.1	0.37	2.0	0.34
9.5	33	5.3	0.88	5.4	0.89	4.8	0.80
10.5	59	3.4	0.53	3.4	0.53	3.0	0.46
11.5	56	2.6	0.53	2.6	0.53	2.2	0.45
12.5	98	2.4	0.43	2.3	0.42	2.0	0.35
13.5	45	3.9	0.79	3.7	0.77	3.0	0.62
14.5	102	2.7	0.37	2.6	0.36	2.1	0.28
15.5	21	3.4	0.76	3.2	0.72	2.5	0.56
16.5	34	6.1	1.5	5.7	1.42	4.4	1.1
17.5	79	3.6	0.64	3.3	0.59	2.5	0.44
18.5	36	3.9	1.1	3.6	0.97	2.7	0.73
19.5	668	3.6	0.15	3.2	0.14	2.4	0.10
20.5	336	4.2	0.27	3.7	0.24	2.7	0.17
21.5	38	5.0	0.77	4.5	0.68	3.3	0.50
22.5	56	2.5	0.47	2.2	0.40	1.6	0.29
24.5	29	3.0	0.49	2.6	0.42	1.9	0.30
25.5	359	4.5	0.25	3.8	0.21	2.7	0.15
26.5	31	3.9	0.60	3.3	0.51	2.4	0.35
27.5	29	6.0	1.3	5.1	1.1	3.6	0.76
28.5	32	10.6	4.7	8.9	3.9	6.2	2.7
29.5	19	3.9	1.1	3.2	0.87	2.3	0.60
30.5	16	6.8	2.2	5.7	1.8	3.9	1.3

For the purpose of convenience the data placed in Tables 5 and 6 are presented in a graphical form in Figures 3 and 4, respectively. It is seen from Tables 5 and 6 as well as from Figures 3 and 4 that during the second half of May the highest estimates of average integrated activity of ^{131}I in thyroid were received according to the first variant of individual thyroid dose calculation and the lowest – according to the third variant of calculation. Figure 5 presents comparison for the same adult person of integrated activity of ^{131}I in thyroid estimated according to the three variants of thyroid dose calculation as a function of date of measurement. It is seen from Figure 5 that at the end of May the estimates according to the first variant are higher comparing to those according to the third variant by factor up to 2.5. The estimates received according to the second variant are much closer to the estimates received according to the third variant and the ratio of those estimates is within the range less than factor of 1.5.

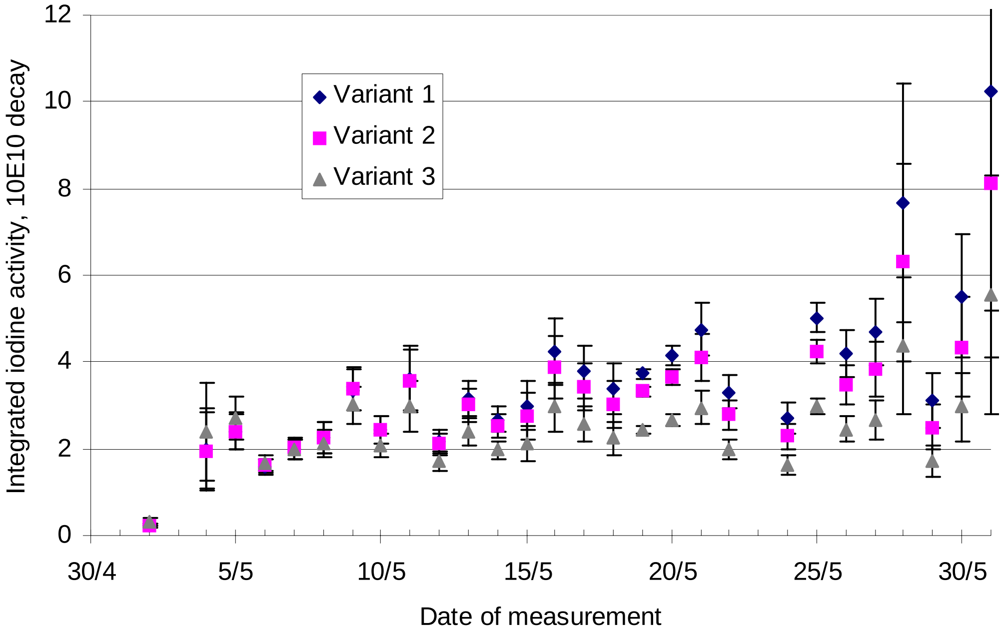


Fig.3. Variation with time of integrated activity of ^{131}I in thyroid averaged for the Gomel residents of all ages for each of the three variants of individual thyroid dose calculation.

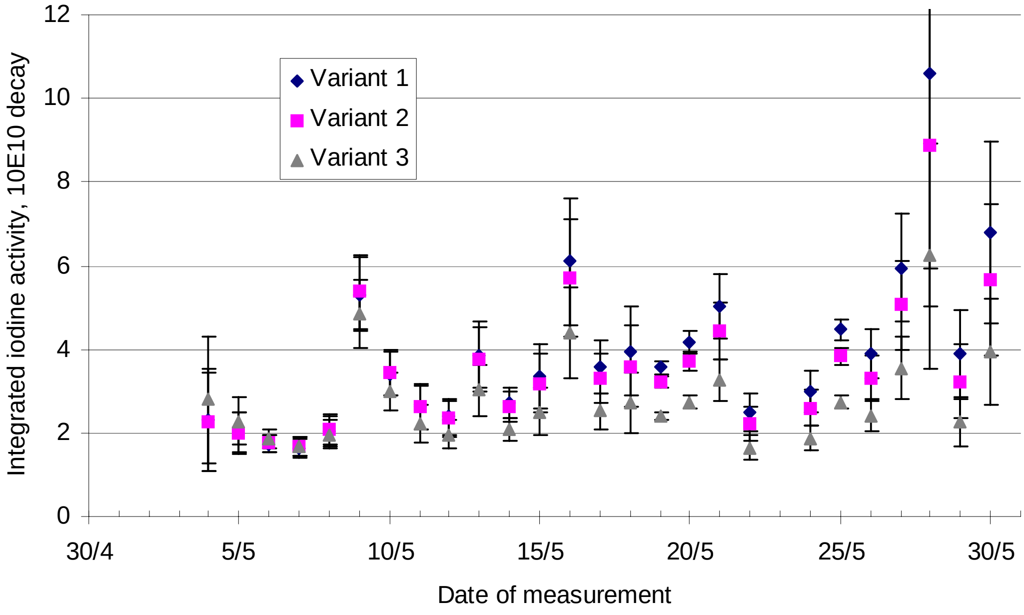


Fig.4. Variation with time of integrated activity of ^{131}I in thyroid averaged for the adult Gomel residents for each of the three variants of individual thyroid dose calculation.

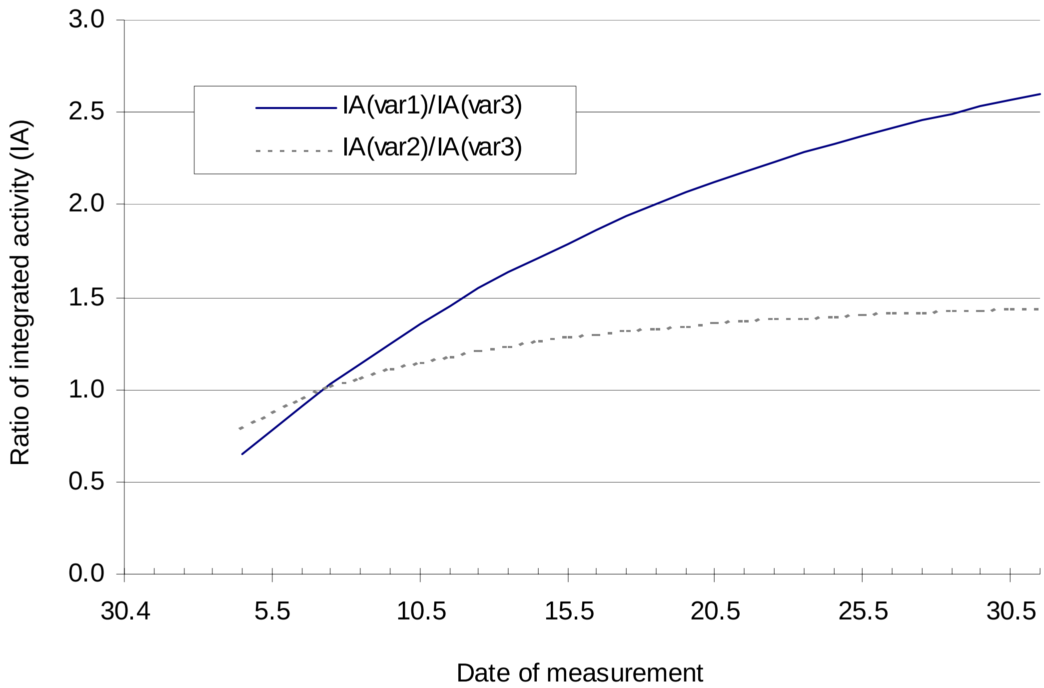


Fig.5. Comparison for the same adult person of integrated activity of ^{131}I in thyroid, IA, estimated according to the three variants of thyroid dose calculation as a function of date of measurement.

Thus, comparison of the estimates of average integrated activity of ^{131}I in thyroid as a function of date of measurement for the three considered variants corresponding to different assumptions regarding radioiodine intake function shows us that the estimates received according to the third variant (assuming radioiodine intake with milk consumption) provide more flatter time dependence function in comparison with the others. In addition, earlier we noticed that for the residents of the other large Belorussian city (Minsk city), who did not leave Minsk city during a few weeks following the accident, we were able to derive empirical intake function based on direct thyroid measurements. That intake function was very close to milk intake function. So, taking into account mentioned above, we accept milk intake function for the Gomel residents who did not leave their city during a few weeks following the accident. Now we will analyze in more detail the time dependence of the estimates of average integrated activity of ^{131}I in thyroid assuming milk intake function (variant 3 of individual thyroid dose calculation). We will analyze it according to two options: (1) without exclusion in a considered set of data of any measurements available and (2) with exclusion in a considered set of data of the outliers, which are determined as measurements, for which the estimates of integrated activity of ^{131}I in thyroid are more than 10 times higher than the estimates of average integrated activity of ^{131}I in thyroid for the same day of measurement. Table 7 presents variation with time of integrated activity of ^{131}I in thyroid, IA, averaged for the residents of all ages and for only adult residents for each of two options: (1) outliers not excluded and (2) outliers excluded. Again, only those average estimates were taken into account for which number of measurements was greater than 10. Figures 6 and 7 present in a graphical form the data placed in Table 7.

Table 7. Variation with time of integrated activity of ^{131}I in thyroid averaged for the Gomel residents of all ages and adults only assuming milk intake function (variant 3 of individual thyroid dose calculation) for two options: (1) outliers not excluded and (2) outliers excluded.

Date of measurement	All ages. Outliers not excluded			All ages. Outliers excluded			Only adults. Outliers not excluded			Only adults. Outliers excluded		
	#	Integrated activity of ^{131}I, IA, 10^{10} decay	Standard error of IA, 10^{10} decay	#	Integrated activity of ^{131}I, IA, 10^{10} decay	Standard error of IA, 10^{10} decay	#	Integrated activity of ^{131}I, IA, 10^{10} decay	Standard error of IA, 10^{10} decay	#	Integrated activity of ^{131}I, IA, 10^{10} decay	Standard error of IA, 10^{10} decay
2.5	23	0.34	0.06	23	0.34	0.06						
4.5	16	2.4	1.1	16	2.4	1.1	12	2.8	1.5	12	2.8	1.5
5.5	87	2.7	0.48	87	2.7	0.48	55	2.3	0.55	55	2.3	0.55
6.5	194	1.7	0.17	194	1.7	0.17	131	1.9	0.21	131	1.9	0.21
7.5	295	2.0	0.23	292	1.7	0.18	212	1.7	0.22	208	1.3	0.15
8.5	197	2.1	0.33	194	1.7	0.20	140	2.0	0.34	138	1.6	0.23
9.5	74	3.0	0.44	74	3.0	0.44	33	4.8	0.80	33	4.8	0.80
10.5	108	2.1	0.27	108	2.1	0.27	59	3.0	0.46	59	3.0	0.46
11.5	84	3.0	0.59	84	3.0	0.59	56	2.2	0.45	56	2.2	0.45
12.5	170	1.7	0.21	168	1.5	0.13	98	2.0	0.35	97	1.7	0.27
13.5	107	2.4	0.32	106	2.2	0.24	45	3.0	0.62	45	3.0	0.62
14.5	164	2.0	0.21	164	2.0	0.21	102	2.1	0.28	102	2.1	0.28
15.5	72	2.1	0.41	71	1.8	0.29	21	2.5	0.56	21	2.5	0.56
16.5	73	3.0	0.55	73	3.0	0.55	34	4.4	1.1	34	4.4	1.1
17.5	130	2.6	0.40	129	2.3	0.31	79	2.5	0.44	79	2.5	0.44
18.5	69	2.2	0.40	68	1.9	0.20	36	2.7	0.73	36	2.7	0.73
19.5	933	2.5	0.09	931	2.4	0.07	668	2.4	0.10	666	2.3	0.07
20.5	444	2.7	0.14	444	2.7	0.14	336	2.7	0.17	336	2.7	0.17
21.5	65	2.9	0.38	65	2.9	0.38	38	3.3	0.50	38	3.3	0.50
22.5	125	2.0	0.24	125	2.0	0.24	56	1.6	0.29	56	1.6	0.29
24.5	43	1.6	0.22	43	1.6	0.22	29	1.9	0.30	29	1.9	0.30
25.5	487	3.0	0.19	485	2.8	0.14	359	2.7	0.15	359	2.7	0.15
26.5	47	2.4	0.30	47	2.4	0.30	31	2.4	0.35	31	2.4	0.35
27.5	54	2.7	0.44	54	2.7	0.44	29	3.6	0.76	29	3.6	0.76
28.5	55	4.4	1.6	54	2.9	0.52	32	6.2	2.7	31	3.7	0.88
29.5	35	1.7	0.35	35	1.7	0.35	19	2.3	0.60	19	2.3	0.60
30.5	28	3.0	0.79	28	3.0	0.79	16	3.9	1.3	16	3.9	1.3
31.5	17	5.5	2.8	17	5.5	2.8						

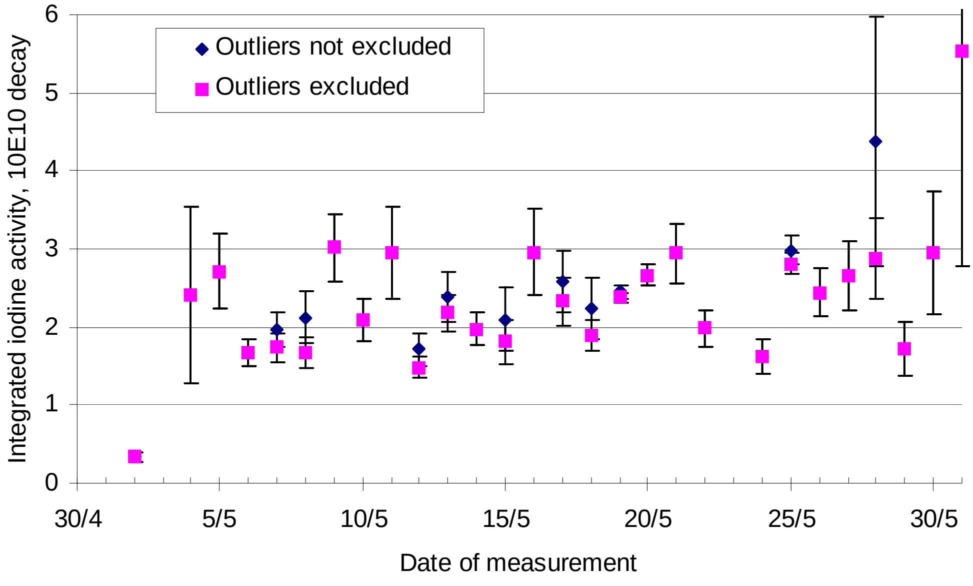


Fig.6. Variation with time of integrated activity of ^{131}I in thyroid averaged for the Gomel residents of all ages assuming milk intake function (variant 3 of individual thyroid dose calculation) for two options: (1) outliers not excluded and (2) outliers excluded.

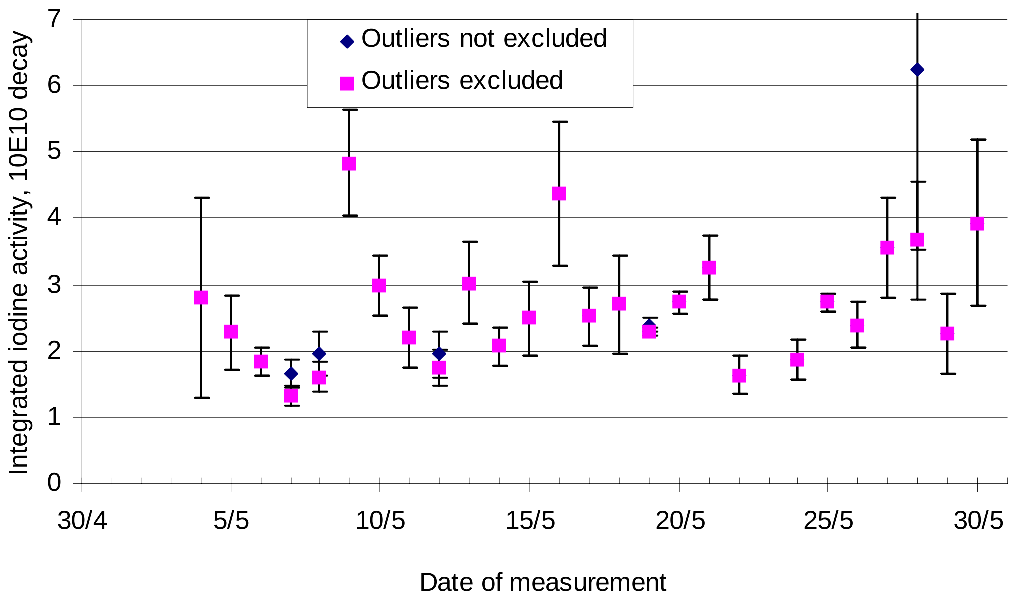


Fig.7. Variation with time of integrated activity of ^{131}I in thyroid averaged for the adult Gomel residents assuming milk intake function (variant 3 of individual thyroid dose calculation) for two options: (1) outliers not excluded and (2) outliers excluded.

Analysis of the time dependencies in Figures 5 and 6 clearly shows that exclusion of outliers leads to receiving almost flat time dependency of estimates of average integrated activity of ^{131}I in thyroid, IA, as for the residents of all ages as for the adults only. It is interesting to see that in Figure 6 exclusion of only one outlier in the set of data for 55 people of all ages measured on May 28 results in decrease of IA from 4.4×10^{10} decay to 2.9×10^{10} decay, i.e. 1.5 times. Exclusion of that outlier resulted in even greater decrease of IA for adults only for the same date (see Figure 7) from 6.2×10^{10} decay to 3.7×10^{10} decay, i.e. 1.7 times. High value of standard error associated with average IA for all ages measured on May 31 (see Figure 6) evidences that this set of data consisting of 17 people likely contains a very high individual estimate of IA though it does not exceed 10 times of the estimate of average IA. Indeed, if we had eliminated the highest individual estimate which is 47×10^{10} decay (it is higher than the average estimate by factor of 8.4) than the rest set of data consisting of 16 people would have been decreased from 5.5×10^{10} decay to 3.0×10^{10} decay, i.e. 1.8 times. In such case all the points in Figure 6 for the option of outliers excluded would be completely flat. Also, one should bear in mind that in our analysis regarding whether time dependency exists or not we have at our disposal only small number of measurements for many dates of measurements. So we should not exclude that some fluctuation of average estimates might have been due to small size of sample available for some specific dates.

Here we are facing again with so called "problem of outliers", which is likely to be the result of the situation when among measured people with life-style and dietary habit typical for a considered settlement some persons happened to be from other settlements, which had been more contaminated than a considered one. Then the measurements of the people who came from the other settlements would be higher than the measurements of the people in a considered settlement and as a matter of fact such persons do not reflect thyroid exposure to the residents of the considered settlement. That is why, we are trying to identify such persons by direct or indirect way and to exclude them from consideration in the assessment of average dose for the people residing in a specific settlement.

Thus, in order to estimate age-dependent average doses for the Gomel residents who did not leave their city during a few first weeks following the accident we will exclude revealed outliers (19 measurements) from the considered set of data (4222 measurements). Old and revised estimates of age-dependent average thyroid doses for the Gomel residents and their comparison are presented in Table 8.

Figure 8 presents estimates of age-dependent average integrated activity of ^{131}I in thyroid derived from the revised estimates of age-dependent average thyroid doses for the Gomel residents.

Table 8. Old and revised estimates of age-dependent average thyroid doses for the Gomel residents and their comparison.

Year of birth	Old estimates			Revised (new) estimates			D_{am}(new)/ D_{am}(old)
	#	D_{am}(old), rad	Standard error of D_{am}(old)	#	D_{am}(new), rad	Standard error of D_{am}(new)	
1986&1985	87	84	8.8	168	**35**	3.7	0.42
1984	58	54	7.0	100	**30**	4.4	0.56
1983	67	74	18	106	**31**	5.1	0.42
1982	51	41	5.8	107	**24**	4.0	0.59
1981	50	53	9.6	102	**23**	3.0	0.43
1980	70	33	3.3	115	**17**	1.5	0.52
1979	45	34	9.2	99	**16**	2.0	0.47
1978	44	24	2.8	79	**12**	1.4	0.50
1977	50	39	10	82	**17**	3.6	0.44
1976	40	15	1.4	72	**8.4**	0.79	0.56
1975	50	21	3.8	81	**11**	1.8	0.52
1974	54	14	1.7	76	**8.6**	1.1	0.61
1973	34	14	2.2	66	**7.4**	1.0	0.53
1972	20	19	5.3	39	**11**	2.6	0.58
1971	24	15	2.0	33	**7.3**	1.1	0.49
1970	32	10	1.1	52	**7.3**	1.1	0.73
1969	29	14	3.4	32	**9.0**	2.0	0.64
1968	31	17	6.2	45	**8.0**	1.4	0.47
Adults	1780	7.3	0.25	2749	**4.2**	0.10	0.58
Total	***2616***			***4203***			

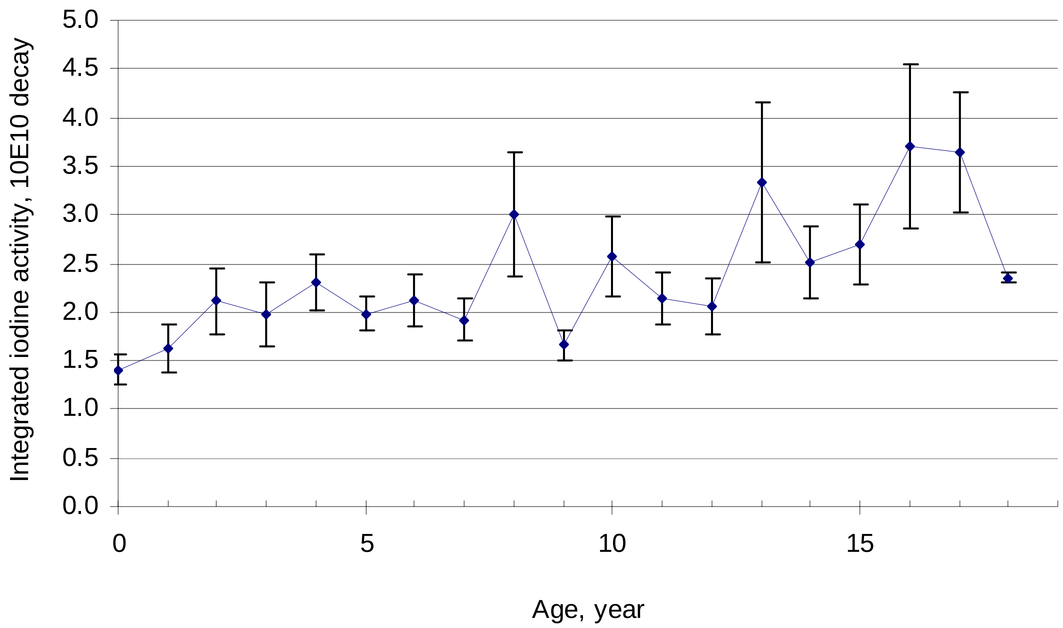


Fig.8. Estimates of age-dependent average integrated activity of ^{131}I in thyroid derived from the revised estimates of age-dependent average thyroid doses for the Gomel residents.

CONCLUSIONS

1. As a result of analysis we changed the method to calculate individual thyroid doses for the Gomel residents and re-evaluated estimates of age-dependent average thyroid doses for those residents. New estimates are approximately two times lower comparing to the previous ones.
2. As distinguished from the old estimates, for the revised thyroid doses there is no tendency "the later measurements were carried out the higher doses were assessed". Practically flat plot of estimates of age-dependent average integrated activity of ^{131}I in thyroid versus date of measurement is observed now for the Gomel residents.

Acknowledgement

This work has been supported by the German Federal Minister of Environment, Nature Preservation and Reactor Safety and the German Federal Office of Radiation Protection under contract number StSch 4240.

ANNEX 5

THYROID DOSE ASSESSMENT FOR THE POPULATION OF MINSK CITY AS A RESULT OF THE CHERNOBYL ACCIDENT

S. Shinkarev[1], Yu. Gavrilin[1], V. Khrouch[1], A. Bouville[2], M. Hoshi[3], P. Jacob[4], R. Meckbach[4], V. Minenko[5], N. Luckyanov[2], S. Tretyakevitch[5], A. Ulanovsky[4,6], P. Voillequé[7]

[1]*State Research Center – Institute of Biophysics, Ministry of Health, Moscow, Russia*
[2]*Division of Cancer Epidemiology and Genetics, National Cancer Institute, National Institutes of Health, Department of Health and Human Services, Bethesda, USA*
[3]*International Radiation Information Center, Research Institute for Radiation Biology and Medicine, University of Hiroshima, Hiroshima, Japan*
[4]*Institute of Radiation Protection, GSF National Research Center, Neuherberg, Germany*
[5]*Belarusian Medical Academy of Continuing Education, Ministry of Health, Minsk, Belarus*
[6]*Joint Institute of Power and Nuclear Research – "Sosny", National Academy of Sciences of Belarus, Minsk, Belarus*
[7]*MJP, Risk Assessment, Inc., Denver, USA*

ABSTRACT

Release of large amounts of radioiodines following the Chernobyl accident on April 26, 1986 resulted in substantial exposure to thyroids for the Belarusian population. A large-scale monitoring of ^{131}I activity in thyroids, encompassing about 130,000 people, including 20,041 residents of Minsk city was conducted in Belarus. Measured ^{131}I activity in thyroid allows the realistic estimate of individual dose to be made with the least uncertainty comparing to that assessed by any other method that is not based on such measurements. The paper describes the methods of individual and collective dose assessment for the Minsk population and presents the current results of this assessment based on the results of thyroid measurements. Analysis of individual doses based on measured ^{131}I activity in thyroid showed that the main contributor to thyroid exposure to environmental ^{131}I for the residents of Minsk city was ingestion of contaminated, fresh milk rather than inhalation of contaminated air. Average thyroid dose for the population living in the city during April-May 1986 was estimated to be: 0.12 Gy for children aged 0 to 6 y; 0.037 Gy for children aged 7 to 17 y and 0.017 Gy for adults. Average thyroid exposure to the Minsk population that left the city in April-May, mainly for the more contaminated areas, was estimated about one order of magnitude higher than that for those who lived in the city. The highest thyroid dose based on direct measurements was found to be 12 Gy for a male born in 1980 who is suspected to have

been to contaminated areas. Current estimate of 50,300 man Gy of collective thyroid dose from ^{131}I for the Minsk population accounts for all the residents including those who left Minsk city for the more contaminated areas in April-May 1986. However, the Minsk residents living in the city in April-May and receiving relatively small thyroid doses provided the main contribution (more than 90%) to the total collective dose for the Minsk population. Distribution of collective dose according to age-group was estimated to be 43% for children aged 0 to 6 y; 20% for children aged 7 to 17y and 37% for adult population.

INTRODUCTION

The accident at the Chernobyl nuclear power plant (NPP) on April 26, 1986 resulted in release into environment of large amounts of radionuclides, including radioiodines, which are of special concern because of their internal exposure to human thyroids. Substantial quantities of radioiodines were deposited on the territory of the Republic of Belarus.

A large-scale monitoring of ^{131}I activity in thyroids of the Belarusian populations (about 130,000 people) mainly in contaminated areas of Gomel and Mogilev Oblasts was conducted within a few weeks following the Chernobyl accident. Besides, the ^{131}I activity in thyroid was measured for more than 20,000 residents in Minsk city. Measured ^{131}I activity in thyroid allows the realistic estimate of individual dose to be made with the least uncertainty comparing to that assessed by any other method that is not based on such measurements. Taking into account that the population of Minsk city is estimated to be 1,510,000 inhabitants (15% of total Belarusian population), it is important to provide estimates of thyroid exposure to the total Minsk population based on the results of reliable estimates for 20,000 residents.

The estimates of thyroid dose from ^{131}I are considered in the paper. The contribution of short-lived radioiodines and of short-lived radiotelluriums to thyroid exposure for the Minsk population was significantly less than that from ^{131}I, accounting for rather late date (April 28, 1986) of the main fallout of radioiodines and the fact that the main intakes of ^{131}I were due to fresh milk consumption.

The purposes of this paper are to (1) describe the methods of individual and collective dose assessment for the Minsk population and (2) present the current results of this assessment.

The estimates of individual dose are being used in ongoing epidemiological study carried out by the Belarusian and American scientists, while the estimate of collective dose can be used in thyroid cancer risk studies.

MATERIALS AND METHODS

Description of the measurements of the ^{131}I content in thyroids of the Minsk city residents

An extensive monitoring of ^{131}I activity in human thyroids was conducted in Minsk city starting from May 1 through June 1986. People were invited to two urban policlinics #5 and #28 where the special measuring points were organized. The SRP-68-01 instruments were used at these measuring points to measure the level of gamma-radiation near the thyroid gland for the purpose of determination the thyroid content, mainly ^{131}I, *in vivo*. Sometimes, such measurement, called "direct" thyroid measurement, was accompanied by the other measurement to take account of background, near the liver, in particular when the measurement near thyroid was relatively high.

The SRP-68-01 instrument has NaI (Tl) scintillation detector and analog output in terms of exposure rate (μR h^{-1}) and count rate (counts per minute). Usually, the indications in μR h^{-1} were recorded as the results of direct thyroid measurements. The instrument measurement error is assessed to be 10% in the 95% confidence interval. The minimum detectable ^{131}I activity at low background level is assesses to be about 1 kBq in the thyroid. The calibration of the instruments was verified before and after the entire measurement campaign.

The Belarusian people coming to the measuring points in the policlinics #5 and #28 were measured regardless whether they were residents of Minsk city or not. The results of thyroid measurement accompanied by the personal information on name, year of birth, place of permanent residence and sometimes, mainly for the Minsk city residents, places where the person temporarily lived in April-May 1986 (if any), were recorded.

People for whom exposure rate measured near the thyroid had exceeded some certain level (that changed with time after the accident) were directed to the Minsk city hospitals for more careful investigation. For the people placed in the hospitals multiple thyroid measurements were conducted during the time they spent there. The SRP-68-01 instruments were also used in the hospitals to carry out these measurements. The results of multiple thyroid measurements in the hospitals accompanied by the same type of the personal information as in the case of the measurements in urban policlinics were recorded.

Dynamics of the direct thyroid measurements of the Minsk residents (20,041 persons, including 7,211 children aged 0 to 17 y) conducted in Minsk city, which were used in individual thyroid dose assessment, is presented in Figure 1.

The most important pathways of ^{131}I intake to thyroid for the Minsk residents living that time in the city were fresh milk bought in urban shops and contaminated air. During the very first days following the accident there was no restriction on delivery of fresh cows' milk produced in the contaminated areas of Belarus to the purchase network of Minsk city. Only at the beginning of May the efforts on radiation monitoring of milk and prohibition of distribution in the purchase network of fresh milk contaminated greater than 3.7 kBq L^{-1} were introduced. According to the data in [1] air contamination with ^{131}I in Minsk city was prolonged with obvious peak occurred on April 28, 1986. Leafy vegetables appeared in the purchase network and at market places at late May and they did not provide any substantial deliver of ^{131}I to the inhabitants.

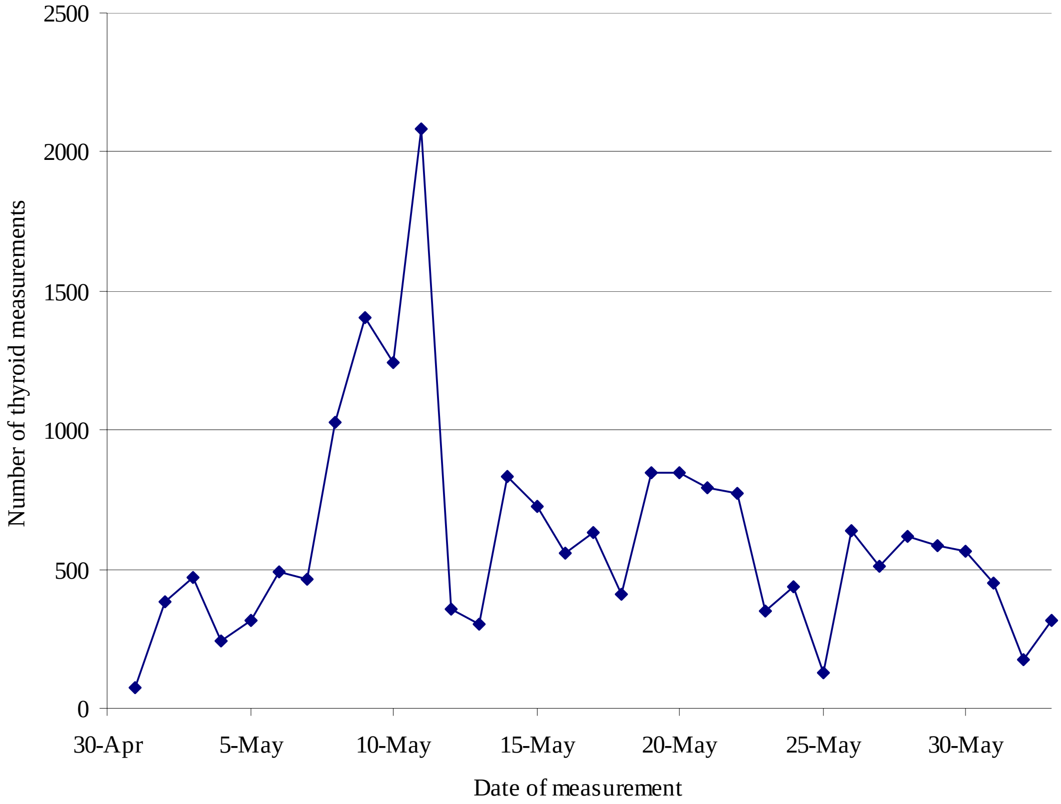


Fig. 1. Dynamics of the direct thyroid measurements of the Minsk residents (20,041 persons, including 7,211 children aged 0 to 17 y) conducted in Minsk city, which were used in individual thyroid dose assessment.

Description of the Minsk population with respect to thyroid exposure from ^{131}I

With respect to thyroid exposure from ^{131}I the population of Minsk city is not homogeneous because part of the residents temporarily lived outside the city for at least several days during the time period from April 26 to May 31, 1986 in the areas where conditions of thyroid exposure were different from that in Minsk. It is worth noting that the above-mentioned time period is the critical one, during which more than 95% of possible ^{131}I intakes had been realized for the overwhelming majority of the Belarusian inhabitants, accounting for a short half-life of ^{131}I (8.04 days) and the main pathways of ^{131}I intakes due to consuming fresh milk and breathing contaminated air. Thus, the Minsk population can be divided at least into two parts according to criterion whether the residents left the city for substantial time during April 26-May 31, 1986. It is necessary to stress that the overwhelming majority of the Minsk population lived in the city during this period of time.

Similar specification was applied to the Minsk residents with direct thyroid measurements and two following groups were formed:

- The first group - people who lived in the city during April 26-May 31; and
- The second group – people who lived outside the city for at least several days during April 26-May 31.

The second group encompasses the three subgroups, which were formed as follows:

- The first subgroup - residents with multiple thyroid measurements conducted in the hospitals for whom the records related to their residing in contaminated areas in April-May 1986 are available;
- The second subgroup - residents with single thyroid measurements conducted in the urban policlinics for whom the records related to their residing outside the city in April-May 1986 are available;
- The third subgroup - residents with single thyroid measurements conducted in the urban policlinics for whom no information on their residing in April-May 1986 is available, but who are assumed to have spent substantial time in contaminated areas in April-May 1986.

The reason to form the third subgroup was as follows. Analysis of distribution of the direct thyroid measurements carried out in policlinics within a day revealed some results that were far beyond the average level. The previous analysis of typical distributions of individual doses for the residents of one settlement from the same age-group showed that as usual more than 95% of the dose estimates are confined within the interval ranging from $D_{gm}/9$ to $9 \times D_{gm}$ (where D_{gm} is geometric mean of the dose distribution) [2]. At the same time it is natural to assume that for some Minsk residents spent substantial time in contaminated areas this information might have not been recorded along the results of their thyroid measurements. To select the people with high results of exposure rate near the thyroid, that were likely to be due to spending some time in contaminated areas, the following criterion was used:

$$P(t_m) > 10 \times P_{am}(t_m) \qquad (1)$$

where

$P(t_m)$ is the exposure rate near the thyroid having subtracted the background level of the person considered on the day of measurement t_m, $\mu R\ h^{-1}$; and

$P_{am}(t_m)$ is the average (arithmetic mean) exposure rate near the thyroid having subtracted the background level for all people measured in the urban policlinics on the day of measurement t_m, for whom no information related to their living outside the city in April-May 1986 is available, μR h^{-1}.

On the contrary to thyroid dose, which severely depends upon age, the exposure rate near thyroid shows a weak dependence on age, so equation (1) can be applied to any person with thyroid measurements regardless of his/her age.

Estimation of individual thyroid dose for the residents with *in-vivo* measurements

General equation to assess individual thyroid dose, D(i), due to internal exposure from β-γ-rays of ^{131}I based on the results of direct thyroid measurements is as follows:

$$D(i) = \alpha \times \frac{E_e(i)}{m(i)} \times G(t_{m,i}) \times F(t_{m,i}) \qquad (2)$$

where

D(i) is the thyroid dose received by a person of age, i;

α is the number of seconds in a day (= 86,400 s d^{-1});

$E_e(i)/m(i)$ is the quotient of the average energy of β-γ radiation absorbed in the thyroid per radioactive decay of ^{131}I, in Joules, and of the mass of the thyroid, in kg; the numerical values of $E_e(i)/m(i)$ are based on data proposed in ICRP Publication 56 [3]. The values of $E_e(i)/m(i)$ are in the range from 1.6×10^{-12} J kg^{-1} per radioactive decay of ^{131}I for the adult to 1.9×10^{-11} J kg^{-1} per radioactive decay of ^{131}I for the newborn;

t_m is the time elapsed from the occurrence of ^{131}I fallout to the date of the thyroid measurements;

$G(t_{m,i})$ is the ^{131}I content in the thyroid at the time of measurement t_m, Bq; and

$F(t_{m,i})$ is the function describing the kinetics of ^{131}I in the human thyroid, d.

The human thyroidal ^{131}I content $G(t_{m,i})$ at the time of measurement t_m was calculated according to the formula:

$$G(t_{m,i}) = k(i) \times [P_{th}(t_m)-k_{body}\times P_{room}(t_m)] \qquad (3)$$

where

k(i) is a calibration coefficient relating the ^{131}I activity in the thyroid to the indication of the SRP-68-01 instrument, Bq h μR^{-1}; the value of k(i) depends on the age, i, of the measured individual;

$P_{th}(t_m)$ is the indication of the instrument during the measurement near the thyroid, μR h^{-1};

k_{body} is a shielding coefficient reflecting the decrease of exposure rate near human body from room background, dimensionless; accepted to be 0.9 for all ages; and

$P_b(t_m)$ is the indication of the instrument during the measurement of room background in the air in the absence of the person, $\mu R\ h^{-1}$.

Taking into account that the thyroid measurements in Minsk city started at the beginning of May, when short-lived radioiodines and radiotelluriums had substantially decayed, it is assumed that, at the time of measurement, t_m, only ^{131}I was present in the thyroid.

The values of the parameter k(i) for adults, k(ad), were determined experimentally [4] and were estimated to be k(ad) = (170±40) Bq h μR^{-1} for the SRP-68-01 instrument. The values of k(i) for people of age i, in years, have been calculated using age-dependent mathematical human phantoms [5] as:

$$k(i) = \frac{k(ad)}{1.64 - 0.0358 \times i} \qquad (4)$$

where

(i) is the age in years of the person considered, y; it is assumed that i=18 for people older than 18 years.

A large number of direct thyroid measurements available for the residents, who lived in the city within a few weeks following the accident (Group 1), has allowed the analysis of time variation of human thyroidal ^{131}I content to be made. The data for adult population, for which the highest number of measurements (11,507) is available, were used to derive this dependence (Figure 2). In Figure 2 the points indicating the average value of the thyroidal ^{131}I content based on the direct thyroid measurements are approximated with an exponential function (curve 2). Besides, two dependences were added to this Figure, assuming ingestion intake of ^{131}I with fresh milk (curve 3) from cows consuming pasture grass starting from April 26 and inhalation of contaminated air (curve 4) on April 28, the date when the main fallout of ^{131}I in Minsk city occurred. The curves 3 and 4 were plotted in such a way to be coincided with curve 2 on May 17 (the middle of the time interval considered). It is seen in Figure 2 that curve 2 is fitted by curve 3 better than that by curve 4, especially in the time interval May 5 – May 25. It is worth noting, that milk sold in urban stores was delivered to the Minsk purchase network from various areas, including contaminated ones. Because the ^{131}I concentration in milk was not monitored within the very first days following the accident it is reasonable to assume that the average concentration of ^{131}I at the end of April – beginning of May was higher than that in the case the countermeasures would have been applied, as it was done at the beginning of May and continued until decay of ^{131}I to negligible level. Thus, if milk pathway had been the most important for the Minsk population, then sharp decrease in average concentration of ^{131}I in milk occurred at the beginning of May would have resulted in the absence of increase of actual dependence at the beginning of May (as it is seen in Figure 2). Also, the countermeasures applied to avoid ^{131}I concentration in milk exceeding temporary level of 3.7 kBq L^{-1} might have resulted to less average value of effective clearance rate of ^{131}I from cows' milk comparing to that in case of no countermeasures were applied. Just this might have been reflected in less sloop of curve 2 comparing to that of curve 3 at late May - beginning of June. Summing up above-mentioned, a conclusion can be done that actual dependence in Figure 2 reflects the prevalence of intake of ^{131}I with fresh milk rather than with inhaled contaminated air.

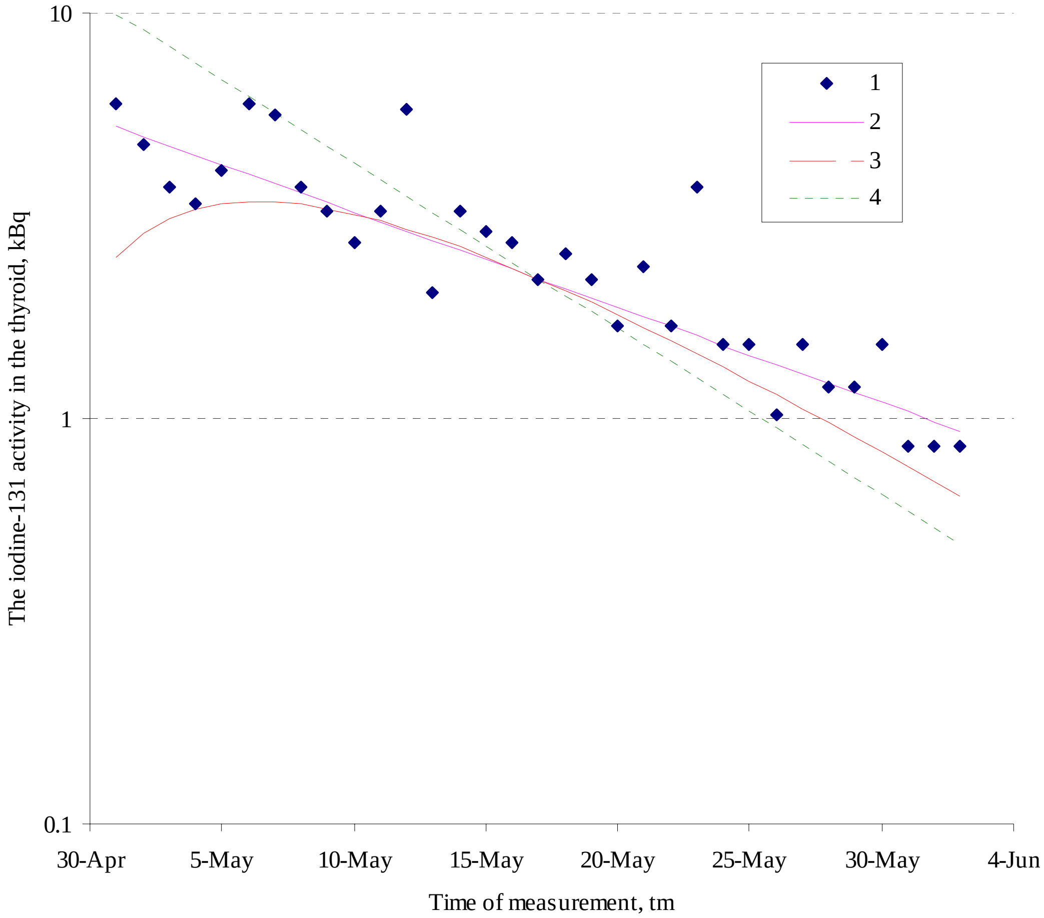


Fig. 2. Variation with the date of measurement of the average value of the ^{131}I activity in the thyroid for an adult population in Minsk city that lived in the city in April-May 1986.
1 - based on the direct thyroid measurements;
2 - approximation of direct measurements with an exponential function;
3 - ingestion intake of ^{131}I with fresh milk is assumed;
4 - inhalation intake of ^{131}I is assumed.

The effective clearance rate of ^{131}I from thyroid derived from curve 2 was estimated to be 0.060 d^{-1} for adults. This estimate is less than the effective rate in the case of a single inhalation intake (0.094 d^{-1}) by factor of 1.57. The following function $F(t_{m,i})$ describing the kinetics of ^{131}I intake by the thyroid of the Minsk resident of any age (i) from Group 1 is assumed

$$F(t_{m,i}) = \frac{k_{minsk}}{\lambda_{th}(i)} \times e^{\frac{\lambda_{th}(i)\times t_m}{k_{minsk}}} \quad (5)$$

where

k_{minsk}=1.57 is an empirically derived coefficient, dimensionless, applicable to the residents of Minsk; and

$\lambda_{th}(i)$ is the effective clearance rate of ^{131}I from the human thyroid, d^{-1}, for a person of age, i; its age-dependent values were derived from those proposed in [3].

For the Minsk residents, who lived in the city in April-May, t_m in equations (2) and (5) is counted from April 28, 1986.

For the Minsk residents who lived outside the city for at least several days during April-May 1986 the procedure to determine function $F(t_{m,i})$ was as follows:

- for the people from first and second subgroups the function $F(t_{m,i})$, typical for the residents of the same age, i, in the settlement where the person considered lived in April-May, was selected. For rural areas milk intake function was typical with variation of the date when fresh milk consumption was ceased. However, if the date of thyroid measurement of the person or the recorded date of his/her coming back to Minsk city was earlier the date when fresh milk consumption was ceased than the date preceding the date of measurement or the date of coming back to Minsk was selected as the date when milk consumption was ceased;
- for the people from subgroup 3 the function $F(t_{m,i})$ assuming intake of ^{131}I with milk, which was ceased on the day preceding the day of thyroid measurement, was selected.

The equation to calculate function $F(t_{m,i})$ assuming intake of ^{131}I with milk is presented below (equation (6)). For the people from third subgroup April 27 was assumed to be the date when the main fallout occurred while the date when the cows were first put on pasture was assumed to be before April 27.

$$F(t_{m,i}) = \frac{e^{\lambda_{th}(i)\times t_m}}{\lambda_{th}(i)} \times \frac{\left[\frac{1}{\lambda_c}\times(1-e^{-\lambda_c t_s}) - \frac{1}{\lambda_g}\times(1-e^{-\lambda_g t_s})\right]}{\frac{1}{\lambda_c-\lambda_{th}(i)}\times\left[1-e^{-(\lambda_c-\lambda_{th}(i))\times t_s}\right] - \frac{1}{\lambda_g-\lambda_{th}(i)}\times\left[1-e^{-(\lambda_g-\lambda_{th}(i))\times t_s}\right]} \quad (6)$$

where

t_s is the time elapsed from the date when the main fallout of ^{131}I occurred in the settlement considered or the date when the cows were first put on pasture (whichever was the last) to the date when milk consumption was stopped, d;

λ_g is the effective clearance rate of ^{131}I from pasture grass, 0.15 d^{-1} [6]; and

λ_c is the effective clearance rate of ^{131}I from cow to milk, 0.63 d^{-1} [6].

Estimation of individual thyroid dose for the residents who lived in the city in April-May 1986 and whose thyroids were not *in-vivo* measured

No correlation was found between the milk consumption rates and the individual doses derived from direct thyroid measurements for the residents of Minsk city included in the first group, thus implying that the ^{131}I milk concentrations were highly variable from one part of the city to another due to fresh milk delivery from various areas of Belarus with different level of ^{131}I fallout. Nineteen age-groups were chosen (18 children age-groups with increment of 1 year starting from zero and one adult age-group for people born earlier 1968).

The two following suggestions have been assumed:

- the persons with direct thyroid measurements included into the first group (who lived in the city in April-May) are representative for the Minsk residents in any age-group who also lived in the city during this time period;
- individual thyroid dose distribution for the residents in each age-group can be approximated satisfactorily with a log-normal function.

Individual thyroid doses for the residents who lived in the city in April-May 1986 and whose thyroids were not *in-vivo* measured were assumed to be equal to the geometric mean of the distribution of thyroid doses based on direct thyroid measurements for the same age category. A geometric standard deviation of the corresponding thyroid dose distribution characterizes the uncertainty of the estimate of individual thyroid dose.

Estimation of collective thyroid dose for the Minsk city population

Collective thyroid dose from ^{131}I for the Minsk population consists of two parts: (1) dose to the residents who lived in the city in April-May 1986 and (2) dose to the residents who lived outside the city for at least several days during April-May 1986. Assessment of collective thyroid dose is carried out separately for each of the three large groups of the population: (1) children aged 0 to 6 y, (2) children aged 7 to 17 y, and (3) adults.

The method to assess collective thyroid dose to population in each of the three above-mentioned groups is the same. Below is considered the method to assess collective thyroid dose to adult population.

The general equation to calculate collective dose can be written as follows:

$$D_{col}(ad) = D_{am,1}(ad) \times N_1(ad) + D_{am,2}(ad) \times N_2(ad) \quad (7)$$

where

$D_{col}(ad)$ is collective thyroid dose to the adult population in Minsk city, man Gy;

$D_{am,1}(ad)$, $D_{am,2}(ad)$ is average dose estimate for adult population that lived in the city in April-May and that lived outside the city for at least several days during that time, respectively, Gy; and

$N_1(ad)$, $N_2(ad)$ is the total number of Minsk adult residents who lived in the city in April-May and who lived outside the city for at least several days during the time, respectively, men.

Assuming that the adults with direct thyroid measurements specified into two groups (first and second) according to conditions of thyroid measurements are representative for those who lived in the city and who left it for at least several days in April-May, one can assume that the estimates $D_{am,1}(ad)$ and $D_{am,2}(ad)$ are equal to the estimates of average dose $D_{am,gr1}(ad)$ and $D_{am,gr2}(ad)$ calculated for adults with direct thyroid measurements included into the first and the second groups, respectively.

The estimate of $N_2(ad)$ can be derived from the number of adults $n_2(ad)$ with direct thyroid measurements in group 2 according to the ratio:

$$N_2(ad) = n_{gr2}(ad) \times (100\% / p_{meas}) \quad (8)$$

where

$n_2(ad)$ is the number of adults with direct thyroid measurements who left the city for at least several days in April-May (the second group), men; and

p_{meas} is the percentage of the adults with direct thyroid measurements in the second group of the total adult population that lived outside the city for at least several days during April-May, %.

The ratio to assess $N_1(ad)$ can be written as follows:

$$N_1(ad) = N(ad) - N_2(ad) \quad (9)$$

where

$N(ad)$ is the total adult population in Minsk city.

RESULTS AND DISCUSSION

Individual thyroid doses for the residents with *in-vivo* measurements

Characteristics of the distribution of individual thyroid doses from ^{131}I based on direct thyroid measurements according to age and conditions of thyroid exposure separately for children aged 0 to 6 y; 7 to 17 y and adults are placed in Tables 1 through 3.

Table 1. Characteristics of the distribution of individual thyroid doses based on direct thyroid measurements for children aged 0 to 6 y.

Group	Number of children	Characteristics of the dose distribution for children born in 1979-1986, Gy				
		10th percentile	Median	Average	90th percentile	Maximum
First	3,742	0.0018	0.057	0.12	0.29	1.6
Second						
Subgroup 1	163	0.24	0.81	1.2	2.6	8.7
Subgroup 2	210	0.021	0.12	0.32	0.86	4.2
Subgroup 3	176	0.36	0.71	1.1	2.4	12
Total	549	0.040	0.50	0.86	2.1	12

Table 2. Characteristics of the distribution of individual thyroid doses based on direct thyroid measurements for children aged 7 to 17 y.

Group	Number of children	Characteristics of the dose distribution for children born in 1968-1978, Gy				
		10th percentile	Median	Average	90th percentile	Maximum
First	2,593	0.0016	0.023	0.037	0.078	0.53
Second						
Subgroup 1	104	0.13	0.49	0.72	1.6	5.1
Subgroup 2	141	0.013	0.057	0.14	0.32	1.4
Subgroup 3	82	0.16	0.29	0.47	0.73	6.6
Total	327	0.021	0.20	0.41	0.90	6.6

Table 3. Characteristics of the distribution of individual thyroid doses based on direct thyroid measurements for adults.

Group	Number of adults	Characteristics of the dose distribution for adults (born earlier 1968), Gy				
		10th percentile	Median	Average	90th percentile	Maximum
First	11,507	0.0010	0.011	0.017	0.038	0.23
Second						
Subgroup 1	382	0.10	0.34	0.49	1.0	4.9
Subgroup 2	559	0.0040	0.025	0.076	0.21	1.3
Subgroup 3	382	0.11	0.18	0.27	0.43	3.4
Total	1,323	0.0092	0.14	0.25	0.56	4.9

It is seen from Tables 1 through 3 that the average thyroid exposure to people living outside the city in April-May 1986 (group 2) is about one order of magnitude higher than that for the residents of Minsk city who did not leave the city within a few weeks after the accident (group 1). Analysis of thyroid exposure to people in the three subgroups within group 2 shows that the highest average dose in this group was estimated for the residents placed in hospitals (subgroup 1) and the lowest for the residents whit single measurements conducted in urban policlinics for whom records are available that they lived in April-May somewhere outside the city (subgroup 2). The highest dose based on direct thyroid measurements was found to be 12 Gy for a male born in 1980 included in subgroup 3 for whom no information on residence history in April-May is available but who is suspected to have been to contaminated areas.

Uncertainties of individual thyroid doses derived from the measurements conducted in policlinics and hospitals in Minsk city are estimated with a geometric standard deviation (GSD) of about 1.8 [7].

Current estimates of average thyroid dose for children from group 1 are higher comparing to our previous estimates published in [8] 0.12 Gy versus 0.08 Gy for children aged 0 to 6 y and 0.037 Gy versus 0.029 Gy for children aged 7 to 17 y but for adults the estimates are almost the same 0.017 Gy versus 0.018 Gy. It is due to use in the current dose assessment of age-dependent parameters (effective clearance of ^{131}I from thyroid and thyroid mass) derived from data proposed in ICRP Publication 56 [3], while the previous dose assessment was based on the values of these parameters published in [6].

Comparison of the average thyroid exposure to the residents in Minsk city (group 1 containing more than 17,000 thyroid measurements) with that to the residents of two other large cities: Gomel (Belarus) [8] and Kiev (Ukraine) [9] where also extensive monitoring of thyroidal ^{131}I content was done (about 5,000 thyroid measurements in each city) shows that according to the level of thyroid exposure to the residents these three cities can be placed as follows Gomel>Kiev>Minsk.

Ratio of the average thyroid dose for children of age i to average thyroid dose for adults among population with direct thyroid measurements who lived in the city in April-May 1986 (first group) as a function of age of children is presented in Figure 3. Two dependences were added assuming intake of ^{131}I due to (1) consuming milk with the same rate for all residents (curve 2) and (2) breathing contaminated air (curve 3).

It is clearly seen from Figure 3 that actual dependence is well fitted by curve 2 assuming intake of ^{131}I with milk and contradicts to the assumption that the main intake of ^{131}I was inhalation of contaminated air. Thus, the dependences in Figure 3 proves that the main contributor to thyroid exposure to environmental ^{131}I for the residents of Minsk city was ingestion of contaminated, fresh milk rather than inhalation of contaminated air.

Individual thyroid doses for the residents who lived in the city in April-May 1986 and whose thyroids were not *in-vivo* measured

A large set of direct thyroid measurements (17,842) available in group 1 has allowed the individual thyroid doses for the other Minsk residents who lived in the city in April-May 1986 and whose thyroids were not *in-vivo* measured to be estimated (Table 4). The geometric mean (GM) of individual dose distributions in each age-group was assumed to be the best estimate for individual dose assessment of the residents without direct measurements. Uncertainty of individual dose assessment expressed as GSD ranges from 2.4 to 2.8 ant is obviously higher than that based on direct thyroid measurements (GSD of about 1.8).

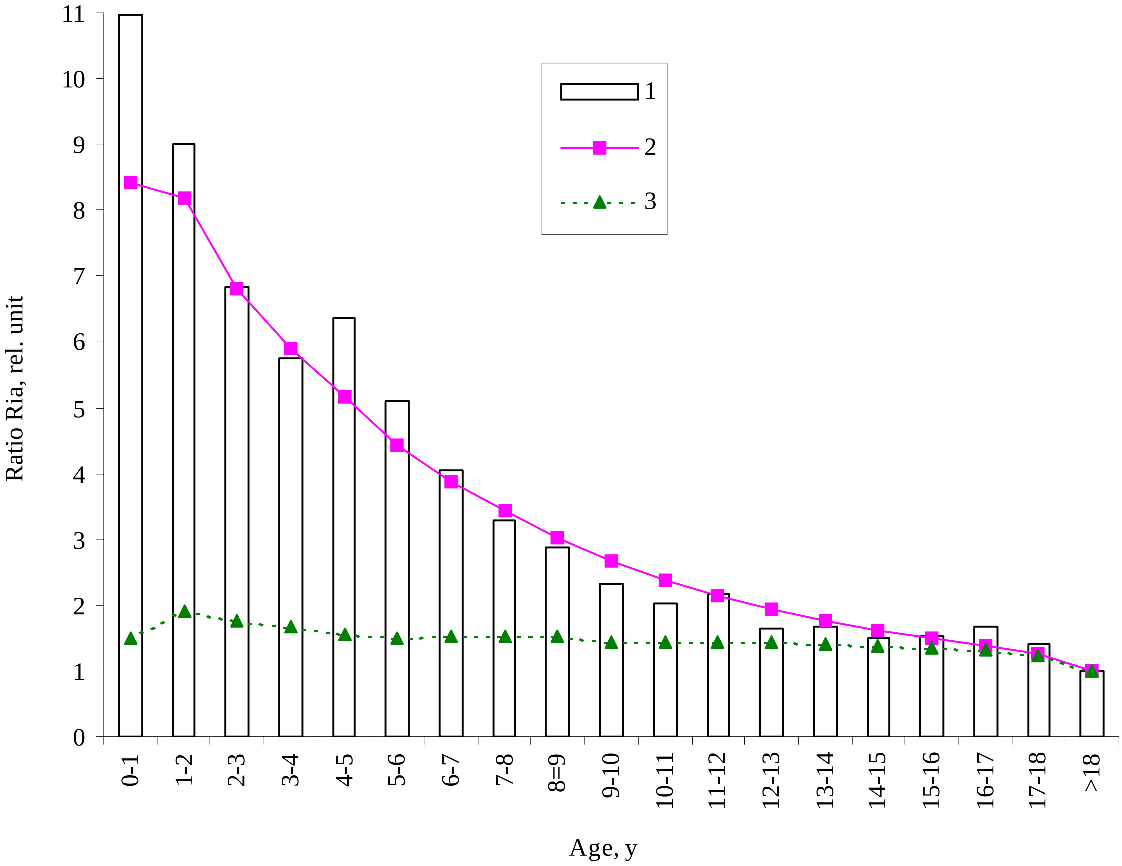


Fig. 3. Ratio of the average thyroid dose for children of age i to average thyroid dose for adults among population with direct thyroid measurements who lived in the city in April-May 1986 (first group) as a function of age of children.
1 - based on direct thyroid measurements;
2 - ingestion intake of ^{131}I with fresh milk is assumed;
3 - inhalation intake of ^{131}I is assumed.

Analysis of the dependence of the GM estimates with age in Table 4 shows the decrease, which is consistent with the theoretical decrease assuming milk intake function for the residents with constant consumption rate regardless of age. Comparison of age-dependences of thyroid exposure for the residents in Minsk and Kiev cities shows some differences. For the Kiev residents average dose for the adults and older children born earlier 1971 was estimated to be 41 mGy (based on 23 thyroid measurements) and it is higher than the estimate of 19 mGy (based on 2,522 thyroid measurements) received for children born in 1971-1978 [9]. Among several reasons to explain such dependence the authors of [9] listed possible changes in nutritional habits, use of stable iodine, temporal living outside Kiev city in April-May etc. It looks like changes in nutritional habits and use of stable iodine were not so widespread in Minsk as it might have been in Kiev, which is located much closer to the Chernobyl NPP comparing to Minsk city.

Table 4. Assessment of individual thyroid dose for those Minsk residents who lived in the city in April-May 1986 and whose thyroids were not *in-vivo* measured.

Year of birth	Number of persons used in assessment	Estimates of individual dose, mGy	
		GM	GSD
1985-1986	548	110	2.8
1984	510	88	2.8
1983	575	67	2.8
1982	559	58	2.7
1981	505	63	2.8
1980	577	54	2.6
1979	468	43	2.6
1978	416	34	2.7
1977	353	32	2.5
1976	345	24	2.7
1975	270	20	2.8
1974	253	23	2.5
1973	239	18	2.4
1972	202	19	2.4
1971	145	16	2.6
1970	150	16	2.7
1969	101	16	2.8
1968	119	15	2.6
earlier 1968	11,507	10	2.8

Collective thyroid dose for the Minsk population

The estimates of collective thyroid dose from ^{131}I for the total Minsk population assuming different values of percentage p_{meas} of measured residents (people in the second group) of total number of the residents who left the city in April-May 1986 are presented in Table 5.

Table 5. The estimates of collective thyroid dose from ^{131}I for the total Minsk population.

Age-group	Population in thousands	Collective dose for different values of parameter p_{meas} (10^3 man Gy)		
		p_{meas} = 70%	p_{meas} = 50%	p_{meas} = 30%
0-6 y	183	21.6	21.9	22.4
7-17 y	260	9.9	9.9	10.1
Adults	1,067	18.3	18.5	18.9
Total	1,510	49.8	50.3	51.4

It is seen in Table 5 that variation of parameter p_{meas} in the range (30-70)% provides a weak influence on the estimate of collective dose for the Minsk population. Estimate of p_{meas}=50% looks like more realistic taking into account that the residents who resided outside Minsk city (especially in areas located close to the Chernobyl NPP) upon their coming back to Minsk in May were very concern with exposure from ^{131}I and they tried to visit measuring points to assess their thyroid exposure. So, the contribution of the Minsk residents living outside the city in April-May to the total collective dose is assessed to be a few percent. Thus, a conclusion can be derived that the Minsk residents living in the city in April-May and receiving relatively small thyroid doses provided the main contribution (more than 90%) to the total collective dose for the Minsk population.

Distribution of collective dose according to age-group was estimated to be 43% for children aged 0 to 6 y; 20% for children aged 7 to 17 y and 37% for adult population.

Current estimate of collective thyroid dose from ^{131}I for the Minsk population 50,300 man Gy is higher than the previous estimate of 41,300 man Gy [10] because of re-assessment of average thyroid doses, mainly for children living in the city in April-May.

Comparison of the estimates of collective thyroid dose for the Minsk population with those calculated for the population of Gomel [10] and Kiev [9] cities shows that according to the value of collective dose the three cities can be placed as follows Kiev (111,000 man Gy for 2,600,000 residents) > Gomel (67,500 man Gy for 488,000 residents) > Minsk (50,300 man Gy for 1,510,000 residents).

CONCLUSIONS

1. The main contributor to thyroid exposure to environmental ^{131}I for the residents of Minsk city was ingestion of contaminated, fresh milk rather than inhalation of contaminated air.
2. Individual doses based on the direct thyroid measurements were estimated for 20,041 residents of Minsk city. The estimates of average thyroid dose for the population living in the city during

April-May 1986 are as follows: 0.12 Gy for children aged 0 to 6 y; 0.037 Gy for children aged 7 to 17 y and 0.017 Gy for adults. The estimates of average thyroid dose for the Minsk population that left the city in April-May, mainly for the more contaminated areas, are about one order of magnitude higher. The highest thyroid dose based on direct measurements was found to be 12 Gy for a male born in 1980 who is suspected to have been to contaminated areas.

3. Current estimate of 50,300 man Gy of collective thyroid dose from ^{131}I for the Minsk population accounts for all the residents including those who left Minsk city for the more contaminated areas in April-May 1986. However, the Minsk residents living in the city in April-May and receiving relatively small thyroid doses provided the main contribution (more than 90%) to the total collective dose for the Minsk population. Distribution of collective dose according to age-group was estimated to be 43% for children aged 0 to 6 y; 20% for children aged 7 to 17 y and 37% for adult population.

REFERENCES

1. Makhon’ko KP, Kozlova EG, Volokitin AA. Dynamics of radioiodine accumulation on soil and reconstruction of doses from iodine exposure on the territory contaminated after the Chernobyl accident. -Radiation and Risk. 7: 140-191; 1996 (in Russian).
2. Khrouch VT, Gavrilin YuI, Shinkarev SM. Correction of individual thyroid dose estimates (calculated earlier using the results of direct thyroid measurements) on the basis of the results of personal interviewing and using the semiempirical formula. Moscow: Institute of Biophysics; Report No. 15-20/95; 1996 (in Russian).
3. ICRP - International Commission on Radiological Protection. Age-dependent doses to members of the public from intake of radionuclides: Part 1. Ingestion dose coefficients. ICRP Publication 56; Ann. ICRP 20(2); 1990.
4. Gavrilin YuI, Khrouch VT, Shinkarev SM. Methodological principles of retrospective assessment of individual internal thyroid doses from radioiodine for Belarussian residents after the Chernobyl accident. Moscow; Institute of Biophysics Report No. B-5029; 1989 (in Russian).
5. Khrouch VT, Gavrilin YuI, Shinkarev SM, Stepanenko VF, Balonov MI, Zvonova IA, Kondrashov AE, Makhon’ko KP, Orlov My, Spirin EV, Isamov NN, Smirnov AB, Ivanova OE, Rusanova GV, Yaskova EK, Petin DV, Moskovko LI, Kim VM, Snykov VP, Khvalensky YuA. Systematizing of thyroid doses for people of Russian territories contaminated as a result of the Chernobyl accident. Report corresponding to contract no 6.5.1.6.2.-96 of Ministry of Emergency; 1996 (in Russian).

6. Arefieva ZS, Badyin VI, Gavrilin YuI, Gordeev KI, Ilyin LA, Kruchkov VP, Margulis UYa, Osanov DP, Khrouch VT. Guidance on thyroid dose assessment for a man due to his radioiodine intake. Edited by Ilyin LA. Moscow: Energoatomizdat Publishing House; 1988 (in Russian).
7. Gavrilin Yu, Khrouch V, Shinkarev S, Drozdovitch V, Minenko V, Shemiakina E, Ulanovsky A, Bouville A, Anspaugh L, Voillequé P, Luckyanov N. Case-control study of Chernobyl-related thyroid cancer among children of Belarus. Part I: Estimation of individual thyroid doses resulting from intakes of ^{131}I, short-lived radioiodines (^{132}I, ^{133}I, ^{135}I), and short-lived radiotelluriums (^{131m}Te and ^{132}Te). Submitted to Health Physics (2002).
8. Gavrilin YuI, Khrouch VT, Shinkarev SM, Krysenko NA, Skryabin AM, Bouville A, Anspaugh LR. Chernobyl accident: reconstruction of thyroid dose for inhabitants of the Republic of Belarus. Health Phys. 76:105-119; 1999.
9. Likhtarev IA, Gulko GM, Kairo IA, Los IP, Henrichs K, Paretzke HG. Thyroid doses resulting from Chernobyl accident Part 1: dose estimates for the population of Kiev. Health Phys. 66:137-146; 1994.
10. Minenko V, Shemyakina E, Drozdovitch V, Shinkarev S, Gavrilin Yu, Khrouch V, Bouville A, Voillequé P. “Chernobyl accident: Assessment of collective thyroid dose for the Belarusian population and comparison with the number of observed thyroid cancers among children”, in: Harmonization of Radiation, Human Life and the Ecosystem, Proceedings (International Radiation Protection Association, Hiroshima, 2000), CD-ROM, Paper No. P-11-263.

RELIABILITY OF ASSESSMENT OF THE INDIVIDUAL THYROID DOSES GREATER THAN 10 GY FOR THE BELARUSIAN POPULATION BASED ON IN-VIVO MONITORING OF IODINE-131 ACTIVITY IN HUMAN THYROIDS FOLLOWING THE CHERNOBYL ACCIDENT

S. Shinkarev[1], Yu. Gavrilin[1], V. Khrouch[1], A. Bouville[2], M. Hoshi[3], R. Meckbach[4], V. Minenko[5], N. Luckyanov[2], A. Ulanovsky[4,6], P. Voillequé[7]

[1]*State Research Center – Institute of Biophysics, Ministry of Health, Moscow, Russia*
[2]*Division of Cancer Epidemiology and Genetics, National Cancer Institute, National Institutes of Health, Department of Health and Human Services, Bethesda, USA*
[3]*International Radiation Information Center, Research Institute for Radiation Biology and Medicine, University of Hiroshima, Hiroshima, Japan*
[4]*Institute of Radiation Protection, GSF National Research Center, Neuherberg, Germany*
[5]*Belarusian Medical Academy of Continuing Education, Ministry of Health, Minsk, Belarus*
[6]*Joint Institute of Power and Nuclear Research – "Sosny", National Academy of Sciences of Belarus, Minsk, Belarus*
[7]*MJP, Risk Assessment, Inc., Denver, USA*

ABSTRACT

The data bank containing the estimates of individual thyroid dose based on *in-vivo* measurements of ^{131}I activity in human thyroids for the Belarusian people (126,261 persons) conducted within a few first weeks following the Chernobyl accident has been analyzed with respect to assessment of the reliability of high estimates (exceeding 10 Gy). The current number of persons with thyroid doses from ^{131}I exceeding 10 Gy calculated on the basis of the results of direct thyroid measurements is estimated to be 331 (77% of them are children aged 0 to 3 years). The analysis showed that the numbers of persons with thyroid doses exceeding 10 Gy predicted on the basis of the main characteristics (geometric mean and geometric standard deviation) of the individual thyroid dose distributions for the areas where high doses were observed agree well with the observed numbers. This confirms the reliability of the number of doses exceeding 10 Gy calculated on the basis of *in-vivo* monitoring of ^{131}I activity in Belarusian people following the Chernobyl accident. The total number of the persons with thyroid doses exceeding 10 Gy in Belarus is estimated to be in the range of 500-700 residents (mostly children aged 0 to 3 years).

INTRODUCTION

The Chernobyl accident on April 26, 1986 resulted in widespread contamination of the environment with radionuclides, including radioiodines, and this led to substantial radiation exposure to thyroids of many people. An extensive monitoring of ^{131}I activity in thyroids encompassing several thousand residents was conducted in Belarus, Ukraine and Russia within a few first weeks following the accident [1-4]. These measurements, called "direct" thyroid measurements, were used to assess the estimates of individual thyroid dose for almost 130,000 Belarusian people [1, 5]. The estimates of individual thyroid dose based on the results of direct thyroid measurements are considered to be the most reliable comparing to the estimates received by any other method, which does not use these results. Anyway, high thyroid doses (especially exceeding 10 Gy) calculated on the basis of direct thyroid measurements require more careful analysis of the reliability of their assessment in order to make sure if such high doses have actually been received by the residents.

The purpose of this paper is to assess the reliability of high estimates (exceeding 10 Gy) of individual thyroid dose calculated for the Belarusian people on the basis of direct thyroid measurements.

The estimates of thyroid dose from ^{131}I are considered in the paper. It is worth noting that a large amount of ^{131}I intake (resulted in high thyroid dose) can be due to consumption either cow's or goat's milk by a person. The contribution of short-lived radioiodines and of short-lived radiotelluriums to thyroid exposure for the people who consumed milk with average rate is estimated to be in the range (1-6)% [6, 7]. Taking into account that as a rule high thyroid dose is associated with milk consumption rate greater than an average rate, one can conclude that the overall contribution of short-lived radioiodines and radiotelluriums to internal thyroid exposure is not higher than a few percent and is negligible comparing to that of ^{131}I.

Analysis of reliability of high thyroid doses is important to decide whether these high estimates calculated on the basis of direct thyroid measurements should be taken into account to assess average age-dependent thyroid doses for the settlements or should be ignored considering them as "outliers". Also, confirmation of reliability of high estimates of individual thyroid dose can help identify the settlements and areas where the populations have actually received the highest exposure to thyroid. Such information can be used in epidemiological studies.

MATERIALS AND METHODS

Description of the Belarusian data bank with individual thyroid doses

A large-scale monitoring of ^{131}I activity in human thyroids of Belarusian people was conducted mainly in contaminated areas of the country in May – beginning of June 1986. Because of the lack of special equipment for rapid monitoring almost all thyroid measurements were done by means of simple devices DP-5 with Geiger-Muller counter as a detector, SRP-68-01 and DRG3-02, which have NaI (Tl) scintillation detectors, with output in exposure rate or count rate. A large number of radiation monitoring teams consisting of employees with different level of experience and skill took part in conducting these measurements. The results of direct thyroid measurements were of various qualities so different uncertainties were attached to them. A detailed description of the measuring campaign in Belarus and of the methods used to assess individual thyroid doses based on direct thyroid measurements is presented in a numerous papers [1, 5-9]. General characteristics of thyroid measurements conducted in Belarus and uncertainties in the estimates of individual thyroid dose based on these measurements according to conditions of measurements are given in Table 1.

Table 1. Characteristics of thyroid measurements conducted in Belarus and uncertainties (expressed as a geometric standard deviation (GSD)) in the estimates of individual thyroid dose based on these measurements according to conditions of measurements.

Group of reliability	Percentage of measurements	Devices	Places of measurements	Conditions of measurements	GSD of thyroid dose
1	3	DRG3-02, SRP-68-01	Hospitals in Minsk and Gomel Cities	Low background. Multiple measurements. Removal of clothes and wash themselves prior to the measurements	1.7-1.8
2	8	SRP-68-01	Medical policlinics #5 and #28 in Minsk City	Low background. Single measurements of the Minsk inhabitants. Low level or absence of surface contamination.	1.7-1.8
3	19	DP-5	Hospitals in Gomel and Mogilev Cities, centers of raions, sanatoria, recreation facilities, pioneer camps etc.	Low background. As a rule removal of clothes and wash themselves prior to the measurements	1.8-2.1
4	70	DP-5	In contaminated settlements	High background. Presence of surface contamination during measuring procedure	2.1-2.6

A special data bank encompassing 126,261 Belarusian people with the results of direct thyroid measurements, data on residence history and dietary habits, as well as the estimates of individual thyroid dose was created [1, 6]. Of the total number of people included into this data bank, 331 persons were estimated to have been received thyroid doses exceeding 10 Gy. Distribution of all people included into this data bank according to the place of residence with indication of the numbers of persons with thyroid dose estimates exceeding 10 Gy is presented in Table 2. Distribution of the persons with the estimates of individual thyroid dose exceeding 10 Gy in the Belarusian data bank according to the place of residence and thyroid dose interval is presented in Table 3.

Table 2. Distribution of all people included into the Belarusian data bank with estimates of individual thyroid dose (D) based on thyroid measurements according to the place of residence with indication of the numbers of persons with thyroid dose estimates exceeding 10 Gy.

Place of residence	Number of the people in the Belarusian data bank			
	total	children	adults	D>10 Gy
Gomel Oblast				
Evacuated settlements of three southern raions: Bragin, Khoiniki, and Narovlya	8103	1804	6299	109
Non-evacuated settlements of three southern raions: Bragin, Khoiniki, and Narovlya	58232	15753	42479	159
Settlements in Loev and Rechitsa raions	14556	5257	9299	30
Settlements in the three northeastern raions: Buda-Koshelev, Korma, and Vetka	4271	1947	2324	8
Gomel City	5613	2249	3364	23
Mozyr City	1470	705	765	1
Total for Gomel Oblast	*92245*	*27715*	*64530*	*330*
Mogilev Oblast				
Settlements in Chericov, Klimovichi, Kostyukovichi, Krasnopolye, and Slavgorod raions	12868	4377	8491	-
Mogilev City	1107	197	910	-
Total for Mogilev Oblast	*13975*	*4574*	*9401*	-
Minsk City	20041	7211	12830	1
TOTAL	**126261**	**39500**	**86761**	**331**

Table 3. Distribution of the persons with the estimates of individual thyroid dose exceeding 10 Gy in the Belarusian data bank according to the place of residence and thyroid dose interval.

Place of residence	Age-group	Number of the people in the thyroid dose intervals					
		>10 Gy -20 Gy	>20 Gy -30 Gy	>30 Gy -40 Gy	>40 Gy -50 Gy	>50 Gy	**Total** (>10 Gy)
Evacuated settlements of three southern raions: Bragin, Khoiniki, and Narovlya	Children 0-6y	59	15	7	1	3	85
	Children 7-17 y	12	1				13
	Adults	10	1				11
Non-evacuated settlements of three southern raions: Bragin, Khoiniki, and Narovlya	Children 0-6y	111	24	7		2	144
	Children 7-17 y	13					13
	Adults	2					2
Settlements in Loev and Rechitsa raions	Children 0-6y	23	4	1			28
	Children 7-17 y	2					2
	Adults						
Settlements in the three northeastern raions: Buda-Koshelev, Korma, and Vetka	Children 0-6y	6	1				7
	Children 7-17 y	1					1
	Adults						
Gomel City	Children 0-6y	21	1				22
	Children 7-17 y						
	Adults	1					1
Mozyr City	Children 0-6y						
	Children 7-17 y	1					1
	Adults						
Minsk City	Children 0-6y	1					1
	Children 7-17 y						
	Adults						
TOTAL	Children 0-6y	221	45	15	1	5	287
	Children 7-17 y	29	1				30
	Adults	13	1				14
	Total	**263**	**47**	**15**	**1**	**5**	**331**

Description of the methods of analysis

Two methods to analyze the reliability of thyroid doses exceeding 10 Gy were applied. The purposes of these methods are slightly different. The purpose of the first method is to assess the number of people with thyroid doses exceeding 10 Gy that is expected to be realized on the basis of analysis of the distribution of individual thyroid doses for the residents from one area encompassing either numerous settlements with similar conditions of thyroid exposure or one settlement and to compare the expected and observed numbers of people. The purpose of the second method is to assess the uncertainty of the estimates of individual thyroid dose exceeding 10 Gy.

The first method is based on a widely spread and experimentally confirmed assumption that individual thyroid dose distribution for the residents in the settlement can be approximated satisfactorily with a lognormal function [6, 10, 11]. Using this assumption, a median of the individual thyroid dose distribution is accepted to be a geometric mean (GM). The value of a GSD is assessed according to the ratio

$$GSD = \sqrt{\frac{p_{84}}{p_{16}}} \quad (1)$$

where

p_{16}, p_{84} are the 16th and 84th percentile of the individual thyroid dose distribution, Gy, respectively.

Based on the estimated values of GM and GSD, the parameter L is assessed as follows:

$$L = \frac{\ln\left(\frac{10Gy}{GM}\right)}{\ln(GSD)} \quad (2)$$

Using the calculated value of parameter L and the tabulated data of integral of probability, the percentile, p(10Gy), corresponding to the thyroid dose of 10 Gy is estimated. Then the expected number of people, n_{exp}, with thyroid doses exceeding 10 Gy in the distribution considered is estimated according to the ratio:

$$n_{exp} = N \times [1 - p(10Gy)/100] \quad (3)$$

where

n_{exp} is the expected number of people with thyroid doses exceeding 10 Gy;

N is the total number of people in the dose distribution;

p(10Gy) is the percentile corresponding to the thyroid dose of 10 Gy in the dose distribution.

The second method implies the analysis of uncertainties attached to the estimates of individual thyroid dose derived from direct thyroid measurements. If multiple measurements are available for one person the analysis of their consistency is carried out.

RESULTS AND DISCUSSION

The first method of analysis was applied to the distributions of individual thyroid dose (D) for children aged 0 to 17 y living in the following areas encompassing numerous settlements with more or less similar conditions of thyroid exposure: (1) evacuated settlements of Bragin, Khoiniki, and Narovlya raions (98 children were found with D>10 Gy) with typical intake of ^{131}I with milk stopped on May 3, 1986, (2) non-evacuated settlements of Bragin, Khoiniki, and Narovlya raions (157 children with D>10 Gy) with typical intake of ^{131}I with milk stopped on May 7, 1986, and (3) settlements in Loev and Rechitsa raions (30 children with D>10 Gy) with typical intake of ^{131}I with milk without any interruption (see Figures 1 through 3). Of 331 persons with thyroid dose estimates exceeding 10 Gy, 285 were found in these three areas (86%). In addition, the first method was also applied to the distributions of individual thyroid dose for children aged 0 to 17 y living in the three settlements (one in each above-mentioned area), namely: (1) evacuated village Pogonnoe in Khoiniki raion (14 children with D>10 Gy), (2) non-evacuated town Narovlya in Narovlya raion (13 children with D>10 Gy), and (3) village Vyshemir in Rechitsa raion (8 children with D>10 Gy) (see Figures 4 through 6).

The results of the analysis of the distributions in Figures 1 through 6 are summarized in Table 4.

It is clearly seen that the distributions plotted in logarithmic scale in Figures 1 through 6 look like normally distributed. Though the three areas (Figures 1 through 3) selected for the analysis were formed taking into account similar intake function for the children, anyway the variation in the fallout level of ^{131}I over these areas resulted in a broad range of individual thyroid doses greater than that in the case of a separate settlement (Figures 4 through 6). The flatter sloop of the left part of the distributions in Figures 2 and 3 probably is explained by prevail of the residents from low contaminated settlements in these areas. That is why in order to predict the number of high doses the values of a GSD for the distributions in Figures 2 and 3 were estimated based on the right part of the distribution according to ratio GSD=p_{84}/GM.

It looks like for town Narovlya (Figure 5) there are two lognormal distributions, the left one is probably due to the residents who did not consume fresh cows' milk (only inhalation intake of ^{131}I was taken place for them). So, to predict the number of high doses only the doses greater than 31.6 mGy ($\log_{10}$(31.6mGy)=1.5) thought to be related to the right peak were used in this analysis.

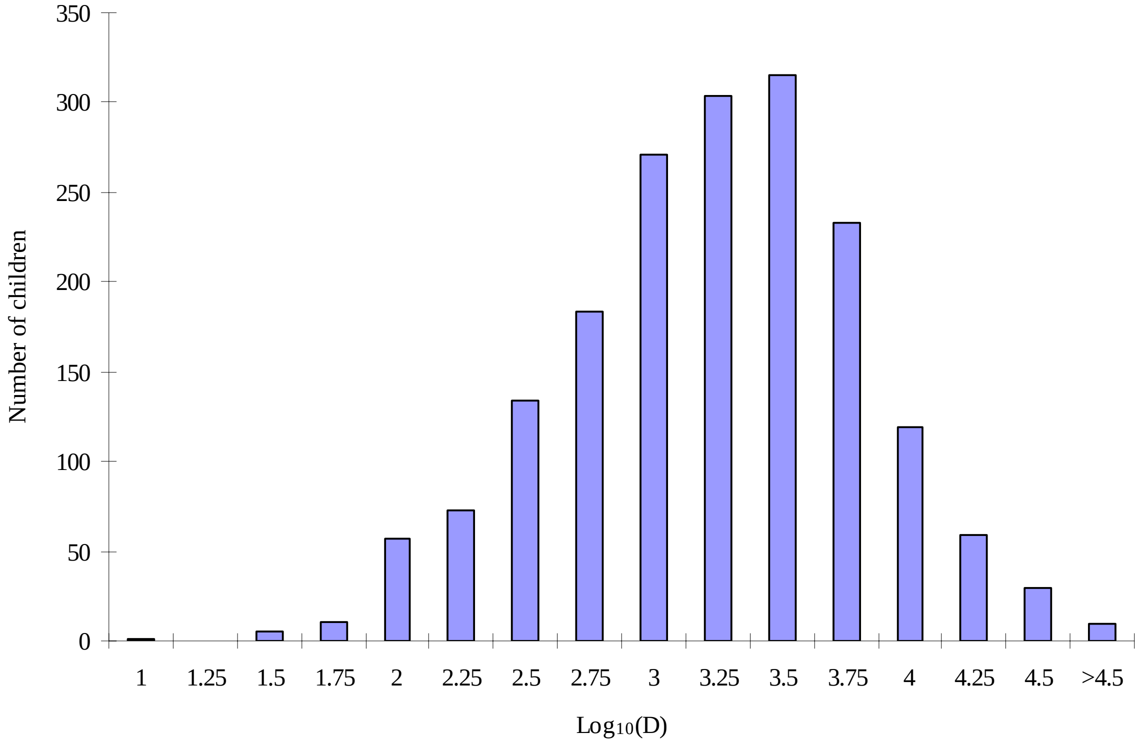


Fig. 1. Distribution of individual thyroid doses (D) for children aged 0 to 17 y from evacuated settlements in Bragin, Khoiniki, and Narovlya raions of Gomel Oblast. Estimates of D are expressed in mGy; $\log_{10}$(10,000mGy)=4.

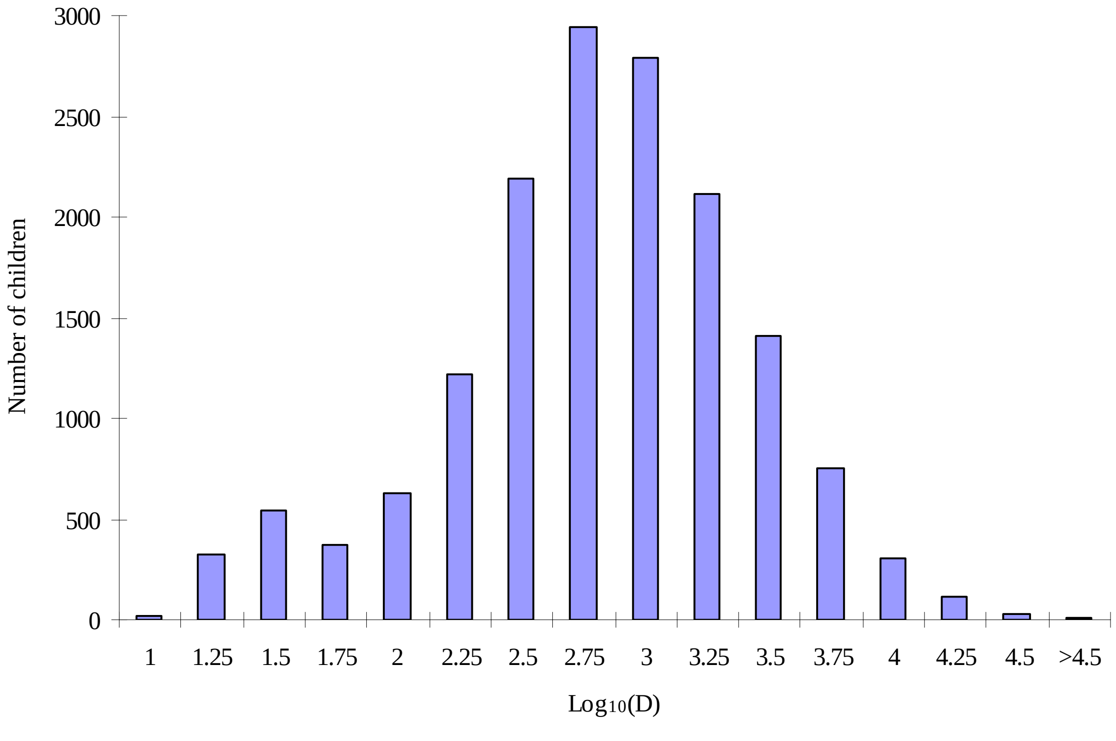


Fig. 2. Distribution of individual thyroid doses (D) for children aged 0 to 17 y from non-evacuated settlements in Bragin, Khoiniki, and Narovlya raions of Gomel Oblast. Estimates of D are expressed in mGy; $\log_{10}$(10,000mGy)=4.

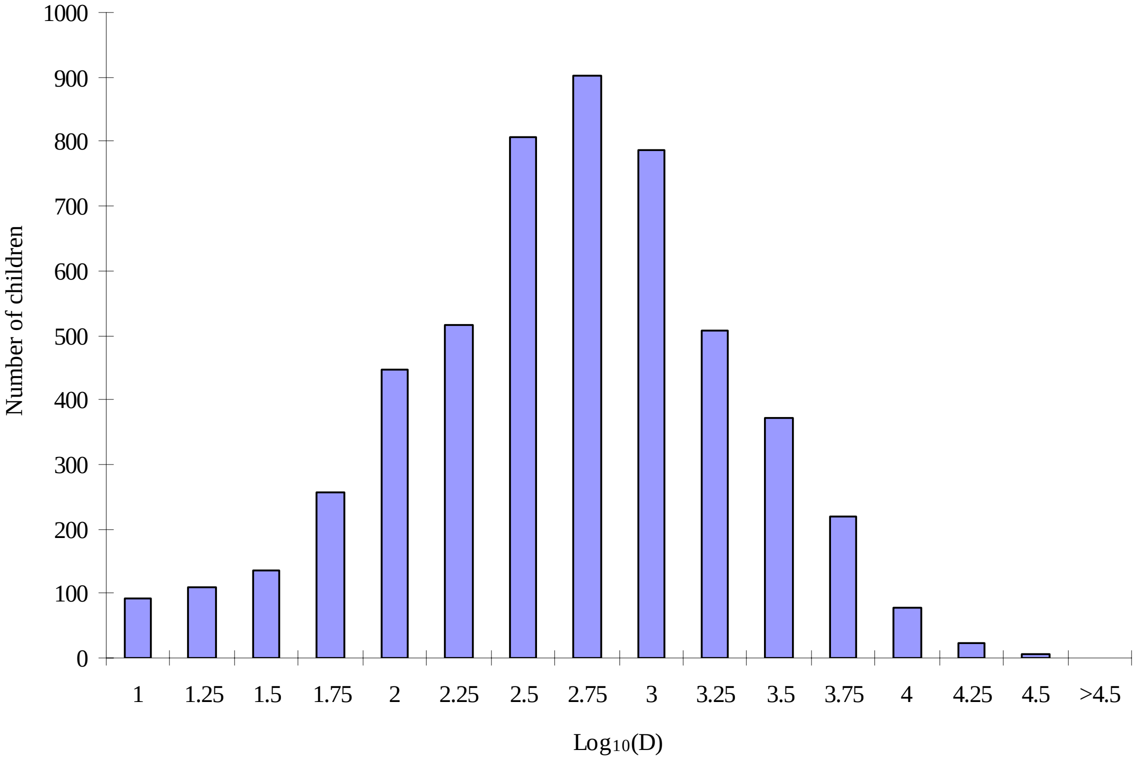


Fig. 3. Distribution of individual thyroid doses (D) for children aged 0 to 17 y from settlements in Loev and Rechitsa raions of Gomel Oblast. Estimates of D are expressed in mGy; $\log_{10}$(10,000Gy)=4.

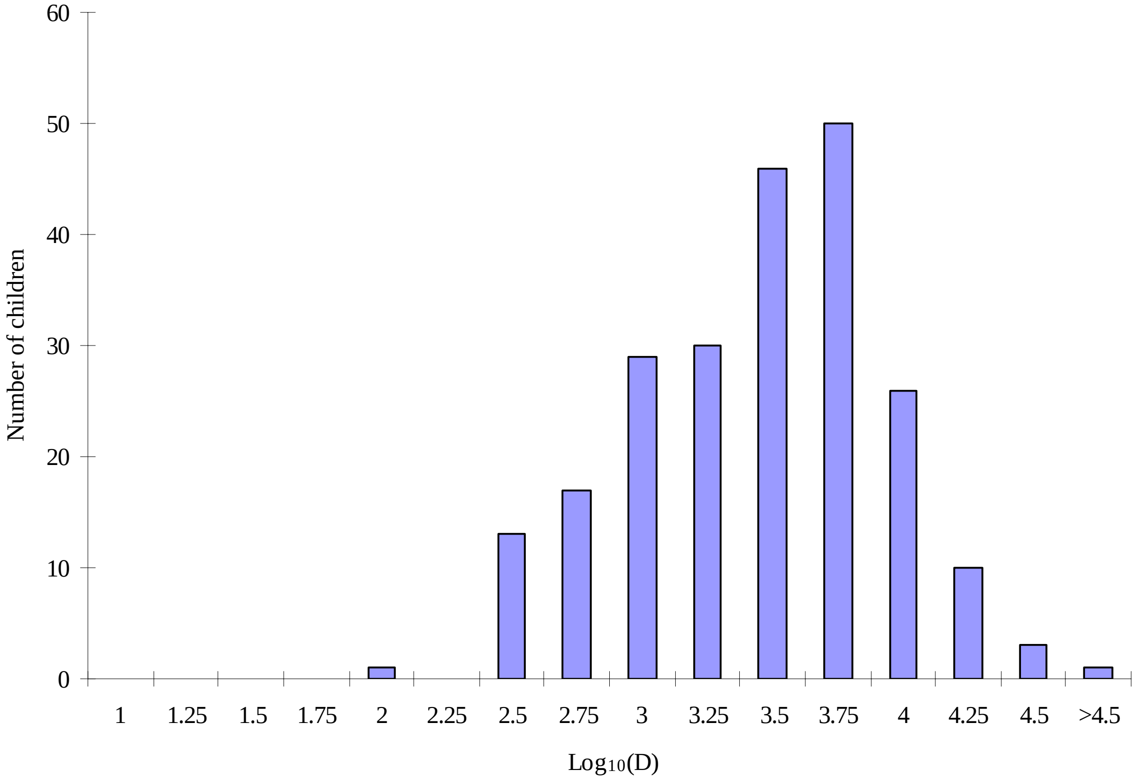


Fig. 4. Distribution of individual thyroid doses (D) for children aged 0 to 17 y from evacuated village Pogonnoe in Khoiniki raion of Gomel Oblast. Estimates of D are expressed in mGy; $\log_{10}$(10,000mGy)=4.

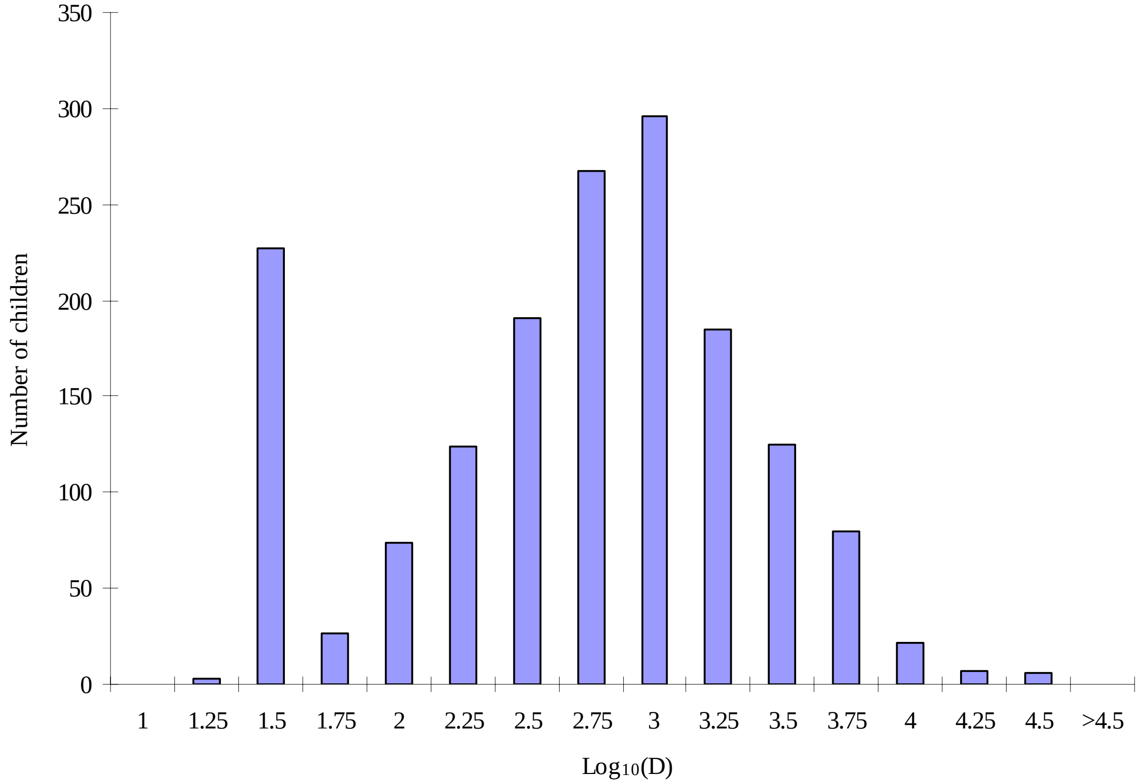


Fig. 5. Distribution of individual thyroid doses (D) for children aged 0 to 17 y from non-evacuated town Narovlya in Narovlya raion of Gomel Oblast. Estimates of D are expressed in mGy; $\log_{10}$(10,000mGy)=4.

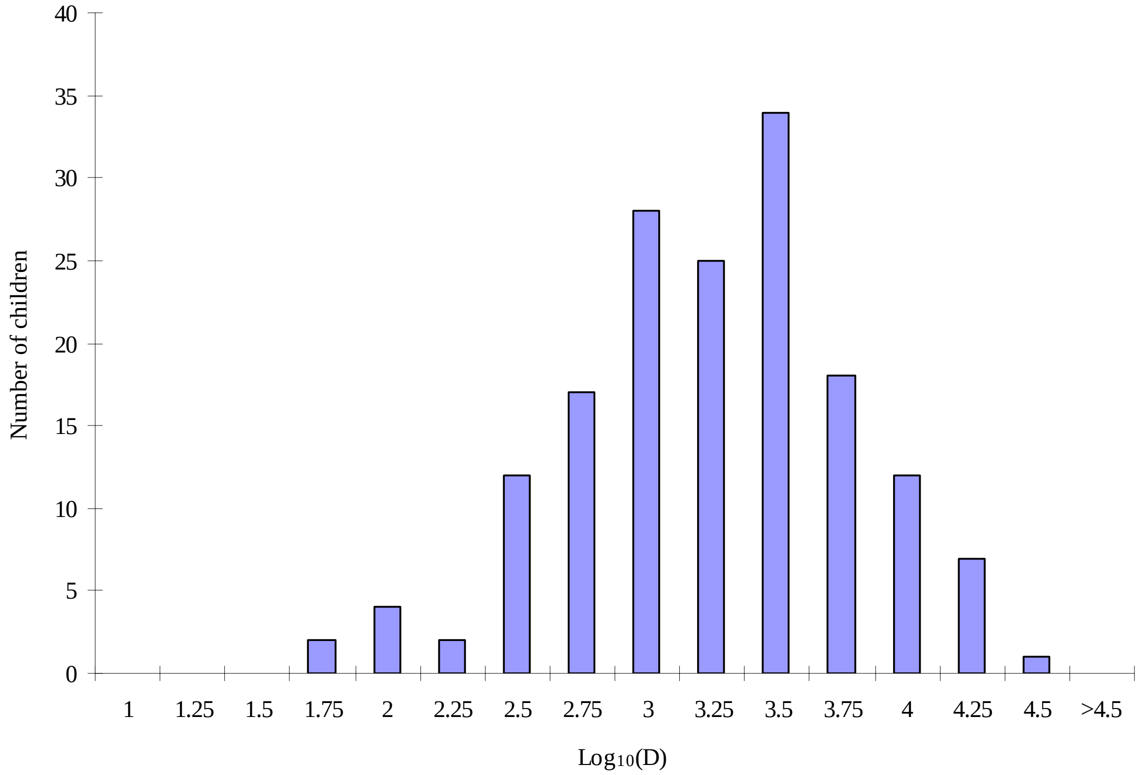


Fig. 6. Distribution of individual thyroid doses (D) for children aged 0 to 17 y from village Vyshemir in Rechitsa raion of Gomel Oblast. Estimates of D are expressed in mGy; $\log_{10}$(10,000mGy)=4.

Table 4. Results of analysis of the individual thyroid dose distributions in Figures 1 through 6 with respect to assessment of the numbers of thyroid doses exceeding 10 Gy and comparison of the expected and observed numbers.

Place of residence	Number of children 0-17y	Characteristics of individual thyroid dose (D) distribution					Number of children with D>10 Gy		Ratio of n_{obs} to n_{exp}
		16th percentile, p_{16}, Gy	Geometric mean GM, Gy	84th percentile, p_{84}, Gy	Geometric standard deviation, GSD	Percentile corresponding to D=10Gy, p(10Gy)	expected, n_{exp}	observed, n_{obs}	
Area encompassing numerous settlements									
Evacuated settlements of three southern raions: Bragin, Khoiniki, and Narovlya	1804	0.326	1.38	4.6	3.76	93.30	121	98	0.81
Non-evacuated settlements of three southern raions: Bragin, Khoiniki, and Narovlya	15753	0.14	0.526	1.83	3.48#	99.09	143	157	1.10
Settlements in Loev and Rechitsa raions	5257	0.082	0.37	1.5	4.05#	99.08	48	30	0.63
Settlement									
Village Pogonnoe in Khoiniki raion	226	0.63	2.3	6.2	3.14	90.05	22	14	0.64
Town Narovlya in Narovlya raion	1404&	0.175	0.57	1.9	3.30	99.18	12	13	1.08
Village Vyshemir in Rechitsa raion	162	0.423	1.5	4.35	3.21	94.81	8	8	1.0

- the estimate of GSD was calculated as follows $GSD=p_{84}/GM$;

& - two peaks were assumed to be in Figure 5; only doses greater than 31.6 mGy ($\log_{10}$(31.6mGy)=1.5) thought to be related to the right peak were analyzed.

Comparison of observed (n_{obs}) and expected (n_{exp}) numbers of individual doses exceeding 10 Gy shows that the ratio n_{obs}/n_{exp} is confined within the range 0.63-1.10 and demonstrates a good consistency of expected and observed numbers for each of the six considered distributions. Taking into account that the observed number of the persons (285 persons) with D>10 Gy in the three considered areas, where analysis has been conducted due to enough statistics, is 86% of total observed number (331 persons), an important conclusion can be derived from the results of the analysis presented in Table 4. The numbers of persons with thyroid doses exceeding 10 Gy predicted on the basis of the main characteristics (geometric mean and geometric standard deviation) of the individual thyroid dose distributions for the areas where high doses were observed based on direct thyroid measurements agree well with the observed numbers. This confirms the reliability of the number of doses exceeding 10 Gy calculated on the basis of direct thyroid measurements.

All the 331 people with the estimates of individual thyroid dose exceeding 10 Gy were distributed according to the group of reliability of thyroid measurements associated with different conditions of measurements and uncertainties attached to the thyroid doses (Table 5). It is naturally to see that the percentage (27%) of the people with D>10 Gy based on multiple thyroid measurements conducted in hospitals (first group of reliability) is about one order of magnitude greater than that (3% see Table 1) among the total number of people with direct thyroid measurements. It is worth noting that for people included into the first and second groups of reliability the overall uncertainty of individual dose is mainly determined by the uncertainty of individual thyroid mass (GSD of 1.6 [12]) rather than the uncertainty associated with direct thyroid measurement (GSD of about 1.4-1.5). On the contrary, for the people included into the third and fourth groups the main contributor to the overall uncertainty in the dose estimate is the uncertainty associated with direct thyroid measurement (GSD up to 1.7-1.8 for the third group and up to 2.2-2.3 for the fourth group [7]).

Table 5. Distribution of the people with the estimates of individual thyroid dose (D) exceeding 10 Gy according to the thyroid dose interval and the group of reliability.

Selection criterion	Number of people	Group of reliability			
		1	2	3	4
10 Gy < D ≤ 30 Gy	310	84	2	133	91
30 Gy < D ≤ 50 Gy	16	5	-	5	6
D > 50 Gy	5	1	-	2	2
Total for D > 10 Gy	331	90	2	140	99

The estimates of individual dose exceeding 10 Gy calculated for 92 persons from the first and second groups of reliability should be considered as reliable. An example of the estimate of individual thyroid dose derived from multiple direct thyroid measurements conducted in the hospital for a child born in 1984 from village Pogonnoe of Khoiniki raion is given in Table 6. It is seen that the four estimates based on the results of four measurements conducted from May 18 to June 2 are consistent and far beyond 10 Gy.

Table 6. Example of assessment of individual thyroid dose based on the multiple measurements conducted in the hospital for a child born in 1984 from evacuated village Pogonnoe in Khoiniki raion.

Date of thyroid measurement in 1986	May 18	May 23	May 28	June 2
Estimate of individual dose, Gy	28	34	48	33
Average estimate of individual dose, Gy	36			

With respect to the estimates of individual dose exceeding 10 Gy calculated for 239 persons included into the third and fourth groups with rather high uncertainties associated to the thyroid measurements it is important to note that the analysis of the places of residence of these people at the time of the accident showed that the majority of them resided in the settlements where also persons from the first group of reliability with D>10Gy were found. This indirectly confirms that such high doses might have been realized for the people included into the third and fourth groups.

Distribution of the people with D>10 Gy according to age at the time of the accident is presented in Table 7. It follows from Table 7 that the children aged 0 to 3 y are about 77% of total number of people with high thyroid doses.

Table 7. Distribution of the people with the estimates of individual thyroid dose exceeding 10 Gy according to age at the time of the accident.

Age at the time of the accident[#], y	<1	1-3	4-6	7-17	Adults	Total
Number of persons	86	170	31	30	14	331

[#] - derived from information on year of birth; e.g. age<1 includes children born in 1986 and 1985

More detail analysis of individual dose estimates with D>30 Gy showed that the highest doses for 15 persons from groups 3 and 4 are under question. The most realistic estimate of the highest thyroid dose in Belarus based on the thyroid measurements is about 50 Gy for children aged 0 to 3 years.

It is important to stress that for the most part of the residents of the cities Gomel, Mozyr, and Minsk with the estimates of thyroid dose exceeding 10 Gy there is information that they resided in contaminated areas, mainly, in Bragin, Khoiniki, and Narovlya raions at the time of the accident. It looks like a high probability exists that the other residents with high doses from these cities also resided outside the cities in contaminated areas at the time.

Taking into account that the major number of high thyroid doses was found in Bragin, Khoiniki, and Narovlya raions of Gomel Oblast where the percentage of measured people is in the interval of (45-70)% [1], the total number of the persons with thyroid doses exceeding 10 Gy in Belarus is estimated to be in the range of 500-700 residents (mostly children aged 0 to 3 years).

CONCLUSIONS

1. The current number of persons with thyroid doses from ^{131}I exceeding 10 Gy calculated on the basis of the results of direct thyroid measurements is estimated to be 331 (77% of them are children aged 0 to 3 years).
2. The numbers of persons with thyroid doses exceeding 10 Gy predicted on the basis of the main characteristics (geometric mean and geometric standard deviation) of the individual thyroid dose distributions for the areas where high doses were observed based on direct thyroid measurements agree well with the observed numbers. This confirms the reliability of the number of doses exceeding 10 Gy calculated on the basis of *in-vivo* monitoring of ^{131}I activity in Belarusian people following the Chernobyl accident.
3. The total number of the persons with thyroid doses exceeding 10 Gy in Belarus is estimated to be in the range of 500-700 residents (mostly children aged 0 to 3 years).

REFERENCES

1. Gavrilin YuI, Khrouch VT, Shinkarev SM, Krysenko NA, Skryabin AM, Bouville A, Anspaugh LR. Chernobyl accident: reconstruction of thyroid dose for inhabitants of the Republic of Belarus. Health Phys. 76:105-119; 1999.
2. Likhtarev I, Sobolev B, Kairo I, Tabachny L, Jacob P, Prohl G, Goulko G. “Results of large scale thyroid dose reconstruction in Ukraine”. In: The radiological consequences of the Chernobyl accident. Proceedings of the first international conference, Minsk, Belarus, 18 to 22 March 1996 (Editors: A. Karaoglou, G. Desmet, G. N. Kelly and H. G. Menzel). European Commission report EUR 16544 EN. Luxembourg; 1996, pp.1021-1034.
3. Zvonova IA, Balonov MI. Radioiodine dosimetry and prediction of consequences of thyroid exposure of the Russian population following the Chernobyl accident. The Chernobyl Papers 1:71-126; 1993.

4. Stepanenko V, Gavrilin Yu, Khrouch V, Shinkarev S, Zvonova I et al. "The reconstruction of thyroid dose following Chernobyl". In: The radiological consequences of the Chernobyl accident. Proceedings of the first international conference, Minsk, Belarus, 18 to 22 March 1996 (Editors: A. Karaoglou, G. Desmet, G. N. Kelly and H. G. Menzel). European Commission report EUR 16544 EN. Luxembourg; 1996, pp.937-948.
5. Gavrilin Yu, Khrouch V, Shinkarev S, Drozdovitch V, Minenko V, Shemyakina E, Bouville A, Anspaugh L, "Estimation of thyroid doses received by the population of Belarus as a result of the Chernobyl accident". In: The radiological consequences of the Chernobyl accident. Proceedings of the first international conference, Minsk, Belarus, 18 to 22 March 1996 (Editors: A. Karaoglou, G. Desmet, G. N. Kelly and H. G. Menzel). European Commission report EUR 16544 EN. Luxembourg; 1996, pp.1011-1020.
6. Shinkarev S, Gavrilin Yu, Khrouch V, Minenko V, Shemyakina E, Tretyakevich S, Bouville A, Voillequé P. "Chernobyl accident: Preliminary estimates of thyroid dose based on direct thyroid measurements conducted in Belarus", in: Harmonization of Radiation, Human Life and the Ecosystem, Proceedings (International Radiation Protection Association, Hiroshima, 2000), CD-ROM, Paper No. P-11-260.
7. Gavrilin Yu, Khrouch V, Shinkarev S, Drozdovitch V, Minenko V, Shemiakina E, Ulanovsky A, Bouville A, Anspaugh L, Voillequé P, Luckyanov N. Case-control study of Chernobyl-related thyroid cancer among children of Belarus. Part I: Estimation of individual thyroid doses resulting from intakes of ^{131}I, short-lived radioiodines (^{132}I, ^{133}I, ^{135}I), and short-lived radiotelluriums (^{131m}Te and ^{132}Te). Submitted to Health Physics (2002).
8. Gavrilin YuI, Khrouch VT, Shinkarev SM. Methodological principles of retrospective assessment of individual internal thyroid doses from radioiodine for Belarussian residents after the Chernobyl accident. Moscow; Institute of Biophysics Report No. B-5029; 1989 (in Russian).
9. Arefieva ZS, Badyin VI, Gavrilin YuI, Gordeev KI, Ilyin LA, Kruchkov VP, Margulis UYa, Osanov DP, Khrouch VT. Guidance on thyroid dose assessment for a man due to his radioiodine intake. Edited by Ilyin LA. Moscow: Energoatomizdat Publishing House; 1988 (in Russian).
10. Simon SL, Lloyd RD, Till JE, Hawtorne HA, Green DC, Rallison ML, Stevens W. Development of a method to estimate thyroid dose from fallout radioiodine in a cohort study. Health Phys. 59:669-691; 1990.
11. Stevens W, Till JE, Thomas DC et al. Report of a cohort study of thyroid disease and radioactive fallout from the Nevada Test Site. University of Utah, Contract N01-C0-23917 NCI, 1992.
12. Dunning DEJr, Schwarz G. Variability of human thyroid characteristics and estimates of dose from ingested ^{131}I. Health Phys. 40:661-675; 1981.

ANNEX 7

Thyroid Exposure of Belarusian and Ukrainian Children due to the Chernobyl Accident and Resulting Thyroid Cancer Risk

Report on

Methodology of assessment of age-dependent average thyroid doses for the settlements in Belarus

FENIX

GSF

November 2001

INTRODUCTION

The basic dosimetry quantity, which is used in the current project, is an estimate of age-dependent arithmetic average thyroid dose for any settlement in Belarus and Ukraine, for which enough number of the residents with direct thyroid measurements is available. In fact, an average estimate is calculated on the basis of individual thyroid doses available in dosimetry databanks in Belarus and Ukraine. In turn, individual thyroid dose comprises internal exposure to thyroid of ^{131}I, and does not include minor exposure due to internal irradiation from short-lived radioiodines and incorporated radiocesiums as well as due to external irradiation.

This report presents description in detail of the methodology of assessment of age-dependent average thyroid doses for the settlements in Belarus. The basis and main features of this methodology is presented in [1].

INPUT DATA

Input data used in assessment of age-dependent average thyroid doses related to each measured individual are as follows:

- individual dose, D_i;
- date of measurement, t_m;
- exposure rate, assigned to ^{131}I thyroidal content at the time of measurement, $P_i(t_m)$;
- date when the main fallout occurred in the vicinity of the settlement considered, t_{fall};
- information from each individual on:
  - the date when he left (if any) the settlement he resided at the time of the accident, $t_{i,left}$;
  - the date when the cow, which milk he consumed, was first put on pasture, $t_{i,cow}$;
- generalized information on the settlement considered on:
  - the typical date when the residents of the same age left (if any) the settlement considered; $t_{set,left}$;
  - the typical date when the cows in the settlement considered were first put on pasture, $t_{set,cow}$.

OUTPUT DATA

Output data of the procedure of assessment of age-dependent average thyroid doses are as follows:

- arithmetic characteristics related to estimate of average dose for the residents in each age-group:
  - arithmetic mean;

- standard error of arithmetic mean;

- geometric characteristics related to estimate of average dose for the residents in each age-group:
  - geometric mean;
  - standard error of geometric mean.

CRITERIA ON SELECTION OF THE SETTLEMENTS WITH DIRECT MEASUREMENTS TO ASSESS AVERAGE THYROID DOSES

We applied the following statistical criteria for making a decision whether available number of direct thyroid measurements for a given settlement is sufficient to assess average thyroid doses for the residents in it:

- the number of the measured residents (adults + children), for whom radioiodine intake with milk was assumed, should be more than 10;
- the number of the measured adults, for whom radioiodine intake with milk was assumed, should be more than 5;

The measured people, for whom we assumed radioiodine intake with milk, were identified as follows:

- exposure rate, assigned to ^{131}I thyroidal content at the time of measurement, should be greater than 0, i.e. $P_i(t_m)>0$;
- the date when the measured person left (if any) the settlement should be later than the date when the main fallout occurred in the vicinity of this settlement and the date when the cow, which milk he consumed, was first put on pasture, i.e. $t_{i,left}>t_{fall}$ and $t_{i,left}>t_{i,cow}$;
- the date of measurement should be later than the date when the cow, which milk he consumed, was first put on pasture, i.e. $t_m>t_{i,cow}$;

Also, we took into account another criterion:

- exposure to thyroid for the measured people should be representative for the typical residents in a given settlement.

The last criterion is important with respect to the measured people resided in large cities in Belarus: Minsk, Gomel, Mogilev, Mozyr. For the Minsk and Gomel cities we managed to select those groups of measured people, whose (in our opinion) thyroid exposure was typical for the residents who did not leave their cities for contaminated areas during the very first weeks following the accident. For the other two cities we failed to do that surely. That is why the average doses were assessed of those four cities, only for Minsk and Gomel.

BASIC CONCEPTIONS

Two exposure routes for radioiodine have been taken into account: (1) ingestion with fresh cows' milk and (2) inhalation of contaminated air. The other exposure routes (e.g. ingestion of leafy vegetables, etc.) are considered to be neglected in comparison with the routes mentioned above.

It was accepted that the rural residents consumed fresh milk locally produced and the pasture-cow-milk food chain was the most significant contributor to ^{131}I exposure to their thyroids. In that case individual thyroid dose estimate (*D*) can be expressed as a linear function of the individual's milk-consumption rate (*V*). In a common view that relationship can be expressed as $\underline{D = a + b \times V}$, where *a* and *b* are coefficients which are derived from the individual doses for a given settlement.

It was assumed that all the parameter values used in the calculations are log-normally distributed. So to describe distribution of the values of each parameter we used log-normal function which is completely determined with: (1) geometric mean (GM) and (2) geometric standard deviation (GSD).

All the population in a settlement is divided into 19 age-groups (one adult category and 18 age-groups for children aged up to 18 y at the time of the accident, with incremental steps of one year).

Thyroid dose to a resident (i), D_i is considered to be the sum of the dose from inhalation, $D_{h,i}$ and the dose from ingestion of milk, $D_{g,i}$:

$$D_i = D_{h,i} + D_{g,i} \tag{1}$$

The arithmetic mean value of the individual inhalation doses for adults, $\overline{D}_{h,a}$ is assumed to be a fraction p_{ad} of the arithmetic mean value of the individual ingestion doses for adults, $\overline{D}_{g,a}$

$$\overline{D}_{h,a} = p_{ad} \times \overline{D}_{g,a} \tag{2}$$

On the basis of the experience from nuclear weapons tests and from measurements related to the Chernobyl accident [2, 3], the value of p_{ad} is taken to be equal to 0.05 for all the villages where inhabitants consumed locally produced milk without any interruption. The inhalation doses for other age categories are derived from the value of $\overline{D}_{h,a}$ (see below), taking into account the differences in breathing rates and in thyroid doses per unit intake.

For a given settlement within a specific age-group for individual passport dose it is assumed:

(1) the value of inhalation dose is the same for the residents; and

(2) the value of ingestion dose is proportional to the individual's milk-consumption rate.

The procedure of calculation of age-dependent average thyroid doses for a selected settlement consists of the following steps:

(1) determination of inhalation doses of ^{131}I for adults and then for children in any age-group;

(2) determination of ingestion doses of ^{131}I for different age-groups on the basis of determination of time-integrated concentration of ^{131}I in milk locally produced in the vicinity of the settlement considered; and

(3) calculation of the total thyroid dose of ^{131}I due to inhalation and ingestion.

DETERMINATION OF INHALATION DOSES

Any individual dose D_i available in databank was estimated according to the intake function described in [4]. For the rural residents thyroid doses were assessed assuming either inhalation or ingestion (with milk) intake. It is necessary to note that if for the person considered ingestion intake was accepted than total thyroid dose was calculated assuming that all ^{131}I was due to milk consumption and ignoring that part of it was due to inhalation. That circumstance is not important for estimation of individual thyroid dose for the persons who consumed milk because inhalation intake contributed very small part of exposure to thyroid. However, in our calculation we should take that into account. Then, available dose estimate, D_i, for individual (i) can be written as a sum of inhalation dose, $D_{h,i}$ and ingestion dose $D_{g,i}$ in such a way:

$$D_i = D_{h,i} \times h_i + D_{g,i} \quad (3)$$

where h_i - correction factor taking into account that D_i was calculated assuming only milk ingestion, rel. unit;

The value of h_i is estimated as follows

$$h_i = F_{ing}(t_m) / F_{inh}(t_m) \qquad (4)$$

where $F_{inh}(t_m)$, $F_{ing}(t_m)$ - the functions describing the kinetics of ^{131}I in the human thyroid, due to inhalation and ingestion intake, respectively, d;

t_m - time of thyroid measurement, d^{-1}.

The values of $F_{inh}(t_m)$ are determined as follows:

$$F_{inh}(t_m) = \frac{e^{\lambda_{th} \times t_{\Delta 1}}}{\lambda_{th}} \qquad (5)$$

where λ_{th} - the effective clearance rate of ^{131}I from the human thyroid, d^{-1}. The values of λ_{th} are presented in Table 1 in APPENDIX;

$t_{\Delta 1}$ - the time duration, calculated from the day of ^{131}I fallout in the vicinity of the settlement to the date of the thyroid measurement, d.

The values of $F_{ing}(t_m)$ are determined as follows [5]:

- if milk interruption occurred before the time of measurement (the date when milk interruption occurred, t_s, was assumed to be the same as the date when the person left the settlement, $t_{i,left}$), i.e. $t_s<t_m$, then

$$F_{ing}(t_m) = \frac{e^{\lambda_{th} \times t_{\Delta 2}}}{\lambda_{th}} \times \frac{\left[\frac{1}{\lambda_c} \times (1 - e^{-\lambda_c t_s}) - \frac{1}{\lambda_g} \times (1 - e^{-\lambda_g t_s})\right]}{\frac{1}{\lambda_c - \lambda_{th}} \times [1 - e^{-(\lambda_c - \lambda_{th}) \times t_s}] - \frac{1}{\lambda_g - \lambda_{th}} \times [1 - e^{-(\lambda_g - \lambda_{th}) \times t_s}]} \qquad (6)$$

where λ_g - the effective clearance rate of ^{131}I from pasture is 0.15 d^{-1};

λ_c - the effective clearance rate of ^{131}I from cow to milk is 0.63 d^{-1};

$t_{\Delta 2}$ - the time duration, calculated from the day of ^{131}I fallout (or from the date when the cow was first put on pasture, if it was after the fallout had occurred) to the date of the thyroid measurement, d.

t_s - the time duration, calculated from the day of ^{131}I fallout (or from the date when the cow was first put on pasture, if it was after the fallout had occurred) to the date when milk interruption occurred, d.

- if milk interruption occurred after the time of measurement, i.e. $t_s \geq t_m$, then

$$F_{ing}(t_m) = \frac{e^{\lambda_{th}\times t_{\Delta 2}}}{\lambda_{th}} \times \frac{\left[\frac{1}{\lambda_c}\times(1-e^{-\lambda_c t_s}) - \frac{1}{\lambda_g}\times(1-e^{-\lambda_g t_s})\right]}{\frac{1}{\lambda_c-\lambda_{th}}\times[1-e^{-(\lambda_c-\lambda_{th})\times t_{\Delta 2}}] - \frac{1}{\lambda_g-\lambda_{th}}\times[1-e^{-(\lambda_g-\lambda_{th})\times t_{\Delta 2}}]} \quad (7)$$

- if milk was consumed without any interruption, then

$$F_{ing}(t_m) = \frac{e^{\lambda_{th}\times t_{\Delta 2}}}{\lambda_{th}} \times \frac{\left(\frac{1}{\lambda_c} - \frac{1}{\lambda_g}\right)}{\frac{1}{\lambda_c-\lambda_{th}}\times[1-e^{-(\lambda_c-\lambda_{th})\times t_{\Delta 2}}] - \frac{1}{\lambda_g-\lambda_{th}}\times[1-e^{-(\lambda_g-\lambda_{th})\times t_{\Delta 2}}]} \quad (8)$$

For the Belorussian settlements, as a rule, the number of measured adults is much greater than that in any other age-group. So distribution of thyroid doses for adults was selected as a basis to estimate inhalation dose to thyroid in any specific group in a settlement. Taking into account eqn(3) it can be written for all adults measured

$$\sum_{i=1}^{n_a} D_{a,i} = \sum_{i=1}^{n_a} h_i \times D_{h,a,i} + \sum_{i=1}^{n_a} D_{g,a,i} = \overline{D}_{h,a} \times \sum_{i=1}^{n_a} h_a + \sum_{i=1}^{n_a} D_{g,a,i} \quad (9)$$

where $D_{a,i}$ - thyroid dose to adult (i), presented in database, Gy;

$D_{h,a,i}$ - inhalation thyroid dose to adult (i), Gy

$D_{g,a,i}$ - ingestion thyroid dose to adult (i), Gy

$\overline{D}_{h,a}$ - arithmetic mean of inhalation doses to adults, Gy;

n_a - number of adults, for whom ingestion intake was assumed.

The term $\sum_{i=1}^{n_a} D_{g,a,i}$ in eqn (9) can be presented as follows:

$$\sum_{i=1}^{n_a} D_{g,a,i} = \sum_{i=1}^{n_a} \overline{D}_{h,a} \times \frac{\overline{D}_{g,a}(\infty)}{\overline{D}_{h,a}} \times \frac{D_{g,a,i}}{\overline{D}_{g,a}(\infty)} = \overline{D}_{h,a} \times r_a \times \sum_{i=1}^{n_a} \omega_{a,i} \quad (10)$$

where $\overline{D}_{g,a}$ - arithmetic mean of ingestion doses to adults, Gy;

$\overline{D}_{g,a}(\infty)$ - arithmetic mean of ingestion doses to adults in case of consuming milk without any interruption, Gy;

$r_a = \frac{\overline{D}_{g,a}(\infty)}{\overline{D}_{h,a}} = 20$ - in accordance with an initial assumption (see eqn(2));

$\omega_{a,i} = \frac{D_{g,a,i}}{\overline{D}_{g,a}(\infty)}$ - correction coefficient which is determined by taking into account the dates of fresh milk consumption for considered adult resident (i).

The values of coefficient $\omega_{a,i}$ as well as the values of similar coefficients $\omega_{j,i}$ for children in (j) age-group are calculated for every settlement depending on the accepted model of radioiodine intake. The formula to estimate the values of $\omega_{a,i}$ ($\omega_{j,i}$) is the same for all residents and depends on only the date when the subject stopped consuming fresh milk, t_s, ($t_s = t_{i,left} - t_{fall}$).

$$\omega_{a,i} = \frac{1}{\lambda_c - \lambda_g} \times [\lambda_c \times (e^{-\lambda_g (t_{i,cow} - t_{fall})} - e^{-\lambda_g t_s}) - \lambda_g \times (e^{-\lambda_c (t_{i,cow} - t_{fall})} - e^{-\lambda_c t_s})] \qquad (11)$$

where if $(t_{i,cow} - t_{fall}) \le 0$, then it is accepted that $(t_{i,cow} - t_{fall}) = 0$.

The dependency of ω_i versus t_s for the case when fallout occurred after the cows had been first put on pasture, ($t_{i,cow} - t_{fall} = 0$), is presented in Figure 1.

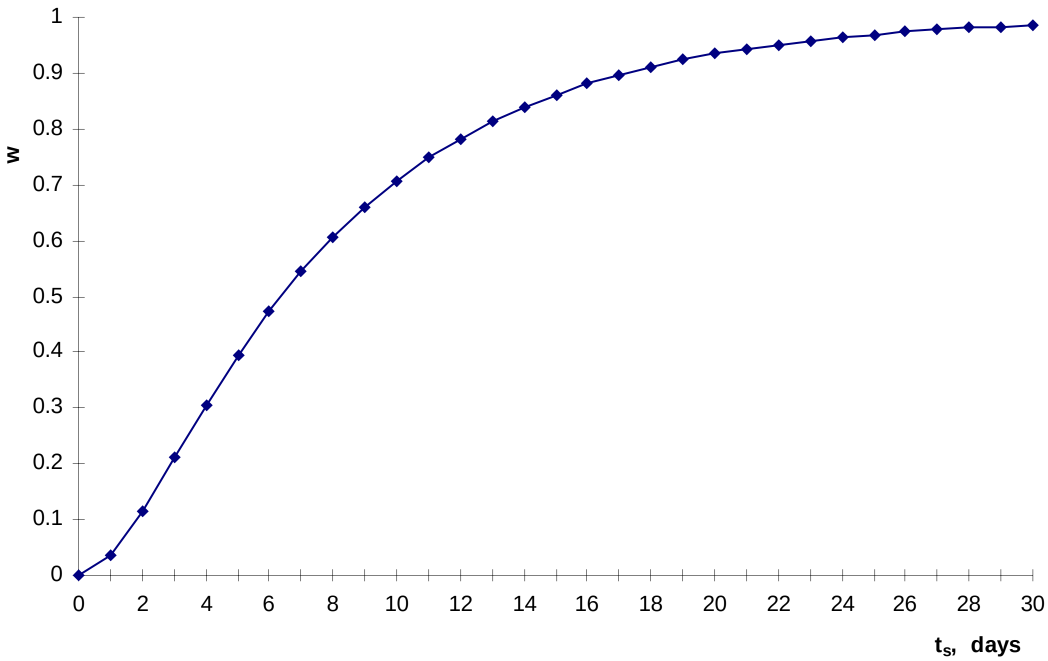


Fig.1. A dependency of correction coefficient ω_i versus duration, t_s, of fresh milk consumption (eqn (11)). That dependency is valid for any individual.

From eqns (9) and (10) the equation to estimate arithmetic mean of inhalation dose for adults can be derived as follows

$$\overline{D}_{h,a} = \frac{\sum_{i=1}^{n_a} D_{a,i}}{r_a \times \sum_{i=1}^{n_a} \omega_{a,i} + \sum_{i=1}^{n_a} h_{a,i}} \tag{12}$$

The value of $\overline{D}_{h,a}$ calculated according to eqn (12) is considered as inhalation dose for any adult in a given settlement. Then average time-integrated ^{131}I concentration in air (C^*_{air}) during the passage of radioactive cloud can be estimated according to the ratio:

$$C^*_{air} = \frac{\overline{D}_{h,a}}{F_{h,a} \times \nu_a} \tag{13}$$

where $F_{h,a}$ - inhalation dose coefficient for ^{131}I intake to adult, Gy Bq^{-1};

ν_a - breathing rate for adult, m^3 s^{-1};

The formula to estimate arithmetic mean of inhalation dose $\overline{D}_{h,j}$ for children in (j) age-group is as follows:

$$\overline{D}_{h,j} = C^*_{air} \times F_{h,j} \times \nu_j = \overline{D}_{h,a} \times \frac{F_{h,j}}{F_{h,a}} \times \frac{\nu_j}{\nu_a} = \overline{D}_{h,a} \times b_j \tag{14}$$

where $F_{h,a}$ - inhalation dose coefficient for ^{131}I intake to children in (j) age-group, Gy Bq^{-1};

ν_a - breathing rate for children in (j) age-group, m^3 s^{-1};

$b_j = \frac{F_{h,j}}{F_{h,a}} \times \frac{\nu_j}{\nu_a}$. The values of coefficient b_j are presented in Table 1 in APPENDIX.

Similarly to the case of adults the value of $\overline{D}_{h,j}$ calculated according to eqn(14) is considered as inhalation dose for any children in a given settlement.

The values of the GSD of inhalation dose distribution for the individuals in any age-group were taken to be the same and equal to β_{D_h} = 2.9 according to the data received in [2]. Then the geometric mean of inhalation dose $D_{h,j}$ for children and adults is estimated by the similar formula:

$$D_{h,j} = \overline{D}_{h,j} \times \exp[-0.5 \times (\ln \beta_{D_{h,j}})^2] \tag{15}$$

DETERMINATION OF INGESTION DOSES

Individual ingestion dose $D_{g,j,i}$ for any individual was calculated according to formula:

$$D_{g,j,i} = D_{j,i} - h_i \times \overline{D}_{h,j} \tag{16}$$

According to the accepted model of iodine intake the value of time-integrated concentration of ^{131}I in fresh milk, $C^*_{milk,j,i}$, consumed by any individual (i) from age-group (j) in a given settlement is estimated as follows:

$$C^*_{milk,j,i} = \frac{D_{g,j,i}}{F_{g,j} \times V_j \times \omega_{j,i}} \tag{17}$$

where $F_{g,j}$ – ingestion dose coefficient for ^{131}I intake to people in age-group (j), Gy Bq^{-1};
V_j - milk-consumption rate for people in age-group (j), L d^{-1};

The values of parameters $F_{g,j}$ and V_j are presented in Table 1.

After estimation of time-integrated concentration of ^{131}I in fresh milk, $C^*_{milk,j,i}$, for each measured individual, for whom we assumed radioiodine intake with milk, the following procedure was used depending on the number of available estimates of $C^*_{milk,j,i}$ for children and adults:

(1) if the number of adults was greater than 10 and the number of children was greater than 10, then the values of arithmetic mean of $C^*_{milk,j,i}$ for adults and children were estimated separately on the basis of the data available for them;

(2) if the number of adults was greater than 10 and the number of children was less than 11, then the value of arithmetic mean of $C^*_{milk,j,i}$ for adults were estimated on the basis of only data for adults but the value of arithmetic mean of $C^*_{milk,j,i}$ for children was assessed on the basis of merged data for adults and children;

(3) if the number of adults was less than 11 then the value of arithmetic mean of $C^*_{milk,j,i}$ for adults and children were estimated on the basis of merged data for adults and children.

The formulas to calculate arithmetic mean value of time-integrated concentration of ^{131}I in milk for children, $\overline{C}^*_{milk,chl}$, and for adults, $\overline{C}^*_{milk,a}$, are as follows:

$$\overline{C}^*_{milk,chl} = \sum_{j=1}^{18} \sum_{i=1}^{n_j} \frac{D_{g,j,i}}{F_{g,j} \times V_j \times \omega_{j,i}} \tag{18}$$

$$\overline{C}^*_{milk,a} = \sum_{i=1}^{n_a} \frac{D_{g,a,i}}{F_{g,a} \times V_a \times \omega_{a,i}} \qquad (19)$$

A very important procedure was incorporated at this stage after assessment of average time-integrated concentration of ^{131}I in milk for adults and children. Here we are facing again with so called “problem of outliers”, which is likely to be the result of the situation when among measured people with life-style and dietary habit typical for a considered settlement some persons happened to be from other settlements, which had been more contaminated than a considered one. Then the measurements of the people who came from the other settlements would be higher than the measurements of the people in a considered settlement and as a matter of fact such persons do not reflect thyroid exposure to the residents of the considered settlement. That is why, we are trying to identify such persons by direct or indirect way and to exclude them from consideration in the assessment of average dose for the people residing in a specific settlement. In order to exclude such outliers the ratios $C^*_{milk,a,i}/\overline{C}^*_{milk,a}$ for adults and $C^*_{milk,j,i}/\overline{C}^*_{milk,chl}$ for children are analyzed. If for some individuals such ratios exceed 10 those measurements are considered to be outliers and are excluded from further procedure. After exclusion of the outliers the average estimates $\overline{C}^*_{milk,a}$ and $\overline{C}^*_{milk,chl}$ are re-calculated again.

Because of full analogy of the further calculation procedure for adults and children of any age-group below are presented the formulas for adults.

The arithmetic standard deviation for distribution of $C^*_{milk,a,i}$ is calculated as:

$$S_{C^*_{milk,a}} = \sqrt{\frac{\sum_{i=1}^{n_a} (C^*_{milk,a,i} - \overline{C}^*_{milk,a})^2}{(n_a - 1)}} \qquad (20)$$

To estimate GM ($C^*_{milk,a,i}$) and GSD ($\beta_{C^*_{milk,a}}$) from the arithmetic mean ($\overline{C}^*_{milk,a,i}$) and the arithmetic standard deviation ($S_{C^*_{milk,a}}$) for the distribution of $C^*_{milk,a,i}$ the following two equations are used:

$$C^*_{milk,a} = \frac{\overline{C}^*_{milk,a}}{\sqrt{1 + \left(\frac{S_{C^*_{milk,a}}}{\overline{C}^*_{milk,a}}\right)^2}} \qquad (21)$$

$$\beta_{C^*_{milk,a}} = \exp\sqrt{\ln\left[1+\left(\frac{S_{C^*_{milk,a}}}{\overline{C}^*_{milk,a}}\right)^2\right]} \quad (22)$$

The value of GM of the ingestion doses for typical adults, $D_{g,a}$, in the considered settlement is assessed as follows

$$D_{g,a} = C^*_{milk,a} \times V_a \times F_{g,a} \times \omega_{a,set} \quad (23)$$

where $\omega_{a,set}$ - correction coefficient which is determined by taking into account the dates of fresh milk consumption for typical adult residents (available information related to $t_{set,left}$ and $t_{set,cow}$ and eqn(11) are used).

The value of GSD for the distribution of the ingestion doses for typical adults, $\beta_{D_{g,a}}$, is calculated as

$$\beta_{D_{g,a}} = \exp\sqrt{(\ln\beta_{C^*_{milk,a}})^2 + (\ln\beta_{m_{th}})^2} \quad (24)$$

where $\beta_{m_{th}}$ - GSD of the distribution of thyroid masses for people in the same age-group. It is accepted to be equal to 1.6.

Arithmetic mean of ingestion dose, $\overline{D}_{g,a}$, and corresponding arithmetic standard deviation, $S_{D_{g,a}}$, for adults are estimated as follows:

$$\overline{D}_{g,a} = D_{g,a} \times \exp[0.5 \times (\ln\beta_{D_{g,a}})^2] \quad (25)$$

$$S_{D_{g,a}} = D_{g,a} \times \exp[0,5 \times (\ln\beta_{D_{g,a}})^2] \times \sqrt{\exp[(\ln\beta_{D_{g,a}})^2] - 1} \quad (26)$$

DETERMINATION OF AGE-DEPENDENT AVERAGE TOTAL DOSES

The equations to calculate arithmetic mean of total dose, $\overline{D}_a$, of ^{131}I for typical adults, arithmetic standard deviation S_{D_a} and standard error of the estimate of arithmetic mean, SE_{D_a}, are as follows

$$\overline{D}_a = \overline{D}_{g,a} + \overline{D}_{h,a} \quad (27)$$

$$S_{D_a} = \sqrt{(S_{D_{g,a}})^2 + (S_{D_{h,a}})^2} \tag{28}$$

$$SE_{D_a} = S_{D_a} \Big/ \sqrt{n_a} \tag{29}$$

The equations to calculate geometric mean of total dose, D_a, of ^{131}I for typical adults, geometric standard deviation β_{D_a} and standard error of the estimate of geometric mean, βE_{D_a}, are as follows

$$D_a = \frac{\overline{D}_a}{\sqrt{1+\left(\frac{S_{D_a}}{\overline{D}_a}\right)^2}} \tag{30}$$

$$\beta_{D_a} = \exp\sqrt{\ln\left[1+\left(\frac{S_{D_a}}{\overline{D}_a}\right)^2\right]} \tag{31}$$

$$\beta E_{D_a} = (\beta_{D_a})^{\frac{1}{\sqrt{n_a}}} \tag{32}$$

REFERENCES

1. Gavrilin, Yu. I., Khrouch, V. T., Shinkarev, S. M. Passportization of the settlements of Gomel region related to the zone of strict control. Assessment of individual thyroid doses for inhabitants. Moscow: Institute of Biophysics; Report No. 46-17-91/B-91-3; 1991 (in Russian).
2. Ng Y.C., Anspaugh L.R., Cederwall R.T. ORERP internal dose estimates for individuals. Health Phys. 59:693-713; 1990.
3. UNSCEAR - United Nations Scientific Committee on the Effects of Atomic Radiation. Exposures from the Chernobyl accident. Annex D in: Sources, effects, and risks of ionizing radiation. 1988 Report to the General Assembly. New York: United Nations; Sales No. E.88.IX.7; 1988:309-374.
4. Arefieva Z.S., Badyin V.I., Gavrilin Yu.I., Gordeev K.I., Ilyin L.A., Kruchkov V.P., Margulis U.Ya., Osanov D.P., Khrouch V.T. Guidance on thyroid dose assessment for a man due to his radioiodine intake. Edited by Ilyin L.A. Moscow: Energoatomizdat Publishing House; 1988 (in Russian).
5. Shinkarev S.M. The methodology used to obtained the initial thyroid dose estimates on the basis of the direct thyroid measurements. Report on Task 1 The distribution of the initial individual thyroid dose estimates that are currently available. BelAm Project. Moscow: April 1997.

Acknowledgement

This work has been supported by the German Federal Minister of Environment, Nature Preservation and Reactor Safety and the German Federal Office of Radiation Protection under contract number StSch 4240.

Table 1. The values of the parameters used in assessment of age-dependent thyroid doses for the Belorussian settlements with sufficient number of direct thyroid measurements.

Year of birth	Effective clearance rate of ^{131}I from the thyroid, λ_{th}, d^{-1}	Ingestion dose coefficient, F_g, Gy Bq^{-1}	Coefficient b, rel. unit	Milk consumption rate, V, L d^{-1}
1986&1985	0.130	37.0	1.4	0.4
1984	0.121	36.0	1.4	0.4
1983	0.116	30.0	1.3	0.4
1982	0.114	25.9	1.2	0.4
1981	0.111	22.7	1.05	0.4
1980	0.108	19.5	1.05	0.4
1979	0.105	17.0	1.05	0.4
1978	0.102	15.1	1.05	0.4
1977	0.099	13.3	1.05	0.4
1976	0.097	11.7	1.05	0.4
1975	0.096	10.4	1.05	0.4
1974	0.096	9.4	1.05	0.4
1973	0.095	8.5	1.05	0.4
1972	0.095	7.7	1.05	0.5
1971	0.095	7.1	1.05	0.5
1970	0.095	6.6	1.05	0.5
1969	0.095	6.1	1.05	0.7
1968	0.095	5.6	1.05	0.7
Adults	0.094	4.4	-	0.7

ANNEX 8

FORM OF PRESENTATION OF THE RESULTS OF ESTIMATES OF AVERAGE AGE-DEPENDENT THYROID DOSES AND ASSOCIATED UNCERTAINTIES IN THYROID DOSES FOR BELARUSIAN SETTLEMENTS WITH MORE THAN 10 MEASUREMENTS OF ^{131}I-ACTIVITIES IN HUMAN THYROIDS.

For each settlement the following information is available:

1) Oblast (English letters)
2) Raion (English letters)
3) Settlement (Russian letters)
4) Settlement (English letters)
5) Settlement code
6) ^{137}Cs ground deposition density
7) Number of measured people:
    a) total
    b) adults
    c) children
8) Group of reliability of the average dose estimates

9) Arithmetic mean dose to thyroid for the residents from “k” age-group
10) Arithmetic standard error of the arithmetic mean dose to thyroid for the residents from “k” age-group
11) Geometric mean dose to thyroid for the residents from “k” age-group
12) Geometric standard error of the geometric mean dose to thyroid for the residents from “k” age-group

Data in bullet 9) through 13) are available for each of 19 age-groups (18 children age-groups with increment of 1 year and one adult group for those who were born before 1968).

ANNEX 9

RESULTS OF ESTIMATION OF AVERAGE AGE-DEPENDENT THYROID DOSES FOR THE CHILDREN POPULATION IN EACH OF THE BELARUSIAN OBLASTS USING DIRECT THYROID MEASUREMENTS AND APPLYING SEMI-EMPIRICAL METHOD.

Table. Average thyroid doses (Gy) in Belarusian oblasts according to the semiempirical model.

	Birth year																	
Oblast/city	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985
Brest	0.022	0.024	0.026	0.027	0.030	0.033	0.036	0.040	0.045	0.051	0.058	0.066	0.075	0.088	0.100	0.116	0.139	0.143
Gomel city	0.080	0.090	0.073	0.073	0.106	0.074	0.086	0.115	0.084	0.171	0.123	0.156	0.170	0.232	0.239	0.309	0.302	0.354
Gomel oblast*	0.154	0.167	0.181	0.195	0.211	0.233	0.258	0.285	0.321	0.365	0.414	0.467	0.535	0.623	0.711	0.823	0.988	1.016
Grodno	0.005	0.005	0.006	0.006	0.007	0.008	0.008	0.009	0.010	0.012	0.013	0.015	0.017	0.020	0.023	0.027	0.032	0.033
Minsk city	0.023	0.028	0.025	0.025	0.028	0.027	0.036	0.034	0.039	0.048	0.055	0.067	0.085	0.106	0.096	0.114	0.150	0.183
Minsk oblast*	0.003	0.004	0.004	0.004	0.005	0.005	0.006	0.006	0.007	0.008	0.009	0.010	0.012	0.014	0.016	0.018	0.022	0.023
Mogilev	0.023	0.025	0.028	0.030	0.032	0.035	0.039	0.043	0.049	0.056	0.063	0.071	0.081	0.095	0.108	0.125	0.150	0.154
Vitebsk	0.001	0.002	0.002	0.002	0.002	0.002	0.002	0.003	0.003	0.003	0.004	0.004	0.005	0.006	0.007	0.008	0.009	0.010

* oblast without capital