Estimation of Thyroid Doses Received by the Population of Belarus as a Result of the Chernobyl Accident

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Abstract. Within weeks of the Chernobyl accident, about 300,000 measurements of human thyroidal ^{131}I content were conducted in the more contaminated territories of the Republic of Belarus. Results of these and other measurements form the basis of thyroid-dose reconstruction for residents of Belarus. Preliminary estimates of thyroid doses have been divided into three classes:
Class 1 ("measured" doses). Individual doses are estimated directly from the measured thyroidal ^{131}I content of the person considered, plus information on life style and dietary habits. Such estimates are available for about 130,000 individuals from the contaminated areas of Gomel and Mogilev Oblasts and Minsk city.
Class 2 ("passport" doses). For every settlement with a sufficient number of residents with "measured" doses, individual thyroid-dose distributions are determined for several age groups and levels of milk consumption. This action has been called the "passportization" of the settlement. A population of about 2.7 million people resides in the "passportized" settlements.
Class 3 ("inferred" doses). For any settlement where the number of residents with "measured" doses is small or equal to zero, individual thyroid doses are derived from the relationship obtained between the mean adult-thyroid dose and the deposition density of ^{131}I or ^{137}Cs in settlements with "passport" doses presenting characteristics similar to those of the settlement considered. This method can be applied to the remainder of the population (about 7.3 million people).
An approximate estimate of the collective thyroid dose for the residents of Belarus is presented. Illustrative results of individual thyroid dose and associated uncertainty are discussed for rural settlements and urban areas.

The Chernobyl accident concerned most of the population of the world. This tragic accident has led scientists from several countries to undertake epidemiological studies in order to clarify the relationship between thyroid dose and thyroid disease, especially for children. In the dosimetric part of such investigations, the main efforts are aimed at reducing the uncertainties associated with the estimation of individual and collective thyroid doses. It is well known that internal radiation exposure of the thyroid from radioiodine (mainly ^{131}I) was the main contributor to the thyroid doses received by the residents of Belarus within the very first weeks after the accident. A large number of measurements of human thyroidal ^{131}I content were conducted in Belarus from the beginning of May to the middle of June, 1986. The results of these measurements, after they were sorted and verified for approximately 200,000 persons, form the basis of the calculation of individual thyroid doses for Belarussian residents. At present about 130,000 individual thyroid doses have been calculated on the basis of the measured thyroidal ^{131}I contents. These doses are called data of Class-1 reliability ("measured" doses). On the basis of the Class-1 data, average thyroid doses have been calculated for the population of more than 800 rural settlements and "passports" have been established for these settlements. The "passportization" of the settlement is a process that allows the assessment of individual thyroid doses (called data of Class-2 reliability or "passport" doses) for the residents of those settlements who were not measured. Such "passports" also have been established for four cities: Minsk, Gomel, Mogilev, and Mozyr. The thyroid doses received by the other residents of Belarus, who are not provided with "measured" or "passport" doses, can be estimated on the basis of the relationship between the ^{131}I or ^{137}Cs ground-deposition density in the area considered and the average thyroid dose obtained from thyroid measurements among residents of that area. Those thyroid doses are called "inferred" doses, or data of Class-3 reliability.

In this paper, the essential features of Class-1, Class-2, and Class-3 data for Belarussian residents are discussed. The currently available results are the outcome of the first stage of the thyroid dose reconstruction in Belarus. They form the basis of the dosimetric support for the epidemiological studies of thyroid disease among Belarussian children that are conducted jointly with American scientists (a retrospective "case-control" study and a prospective cohort study). Some of the key aspects of thyroid dose reconstruction in Belarus also have been presented, mainly in Russian, in scientific publications and in scientific meetings [1-5]. In addition, an extensive discussion, in Russian, of the work done from 1988 to 1993 can be found in the Appendices to a report of the Institute of Biophysics (Moscow) [6].

1. "Measured" individual thyroid doses (data of Class-1 reliability).

The main steps that were followed in the calculation of "measured" doses are presented in Table 1. The total number of Belarussian residents who were measured in May-June of 1986 is not known with accuracy. This is due in particular to the fact that in some measuring stations the residents with values of dose rate near the thyroid lower than some predetermined level (100, 200, 300, or 1000 $\mu R\ h^{-1}$) were not registered. Also, the reliability of the Class-1 data is not uniform because the uncertainty of the measured thyroidal ^{131}I content depends on the measuring conditions and on the measurement device (DP-5, or SRP-68-01, or DRG3). Therefore, the "measured" doses were divided into 3 subgroups of reliability, according to the level of uncertainty associated with the determination of the ^{131}I content in thyroid, characterized with geometric standard deviations of 1.3, 1.7, and 2.2, respectively. The thyroid dose calculation was performed according to a Guidance report [7], assuming ^{131}I intake with inhalation and with ingestion of fresh milk following a single deposition of fallout on pasture grass. The latter way of ^{131}I intake is considered to be predominant for most individuals. The variation with time of the radioiodine deposition, as recorded in stations of the Gidrometeorology Committee, is shown in Fig.1 [8]. It can be seen in Fig.1 that radioiodine fallout in the cities of Gomel, Mogilev, and Grodno occurred mainly over a period of one to two days. This justifies the assumption of a single radioactive fallout in the first stage of calculation of "measured"

Table 1. Description of the main steps followed in the calculation of the data of Class-1 reliability ("measured" individual thyroid doses).

Dates	Type of activity	Result
End of April and beginning of May 1986	Organization of large scale measurements of human thyroidal ^{131}I content	35 measuring groups; measuring stations in the centers of oblasts
May and June 1986	Monitoring the ^{131}I content in the thyroids to reveal the Belarussian residents that were highly exposed	About 300,000 people were examined
1987 - 1988	Collection of original records of measurements of thyroidal ^{131}I content	About 200,000 records
1988	Interviewing inhabitants on lifestyle and diet (levels of milk consumption)	About 150,000 records
1988 - 1989	Verification of results of in vivo thyroid measurements; development of special ways to correct some original data	Three groups of reliability of available measurements; ways of correcting some original data
1988 - 1991	Creating the database of the direct thyroid measurements; development of computer codes for thyroid dose estimation	Data bank containing "measured" individual thyroid doses for 130,000 residents, who had been measured before June 6, 1986

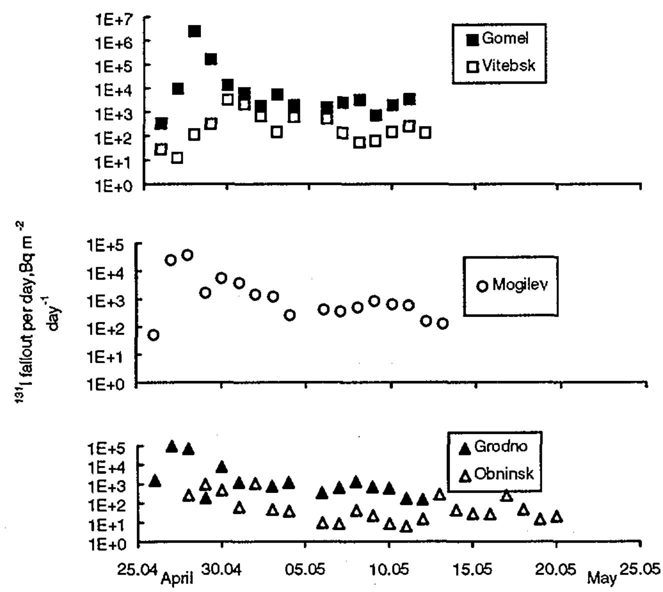

Fig.1. Daily ^{131}I fallout recorded in some observation points of the Gidrometeorology Committee according to the data of SPA "Taifun".

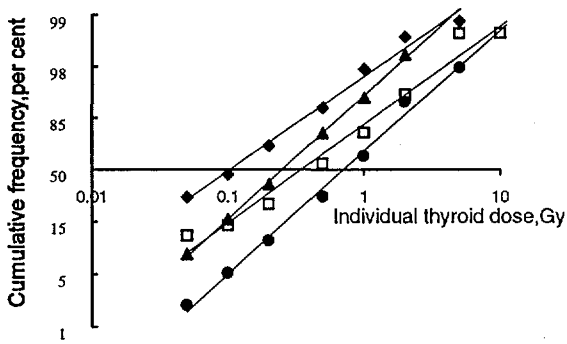

Fig.2 Lognormal probability plot of "measured" individual thyroid doses for adult residents in rural settlements: in Hoiniki raion - Korchevoe (♦), and in Bragin raion - Kolybany (Y); Savichi (▲); Mikhalevka (●)

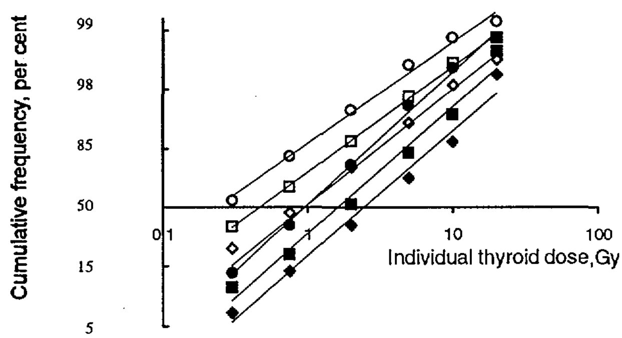

Fig.3 Lognormal probability plot of "measured" individual thyroid doses for the residents in Hoiniki raion: evacuated people - (♦)children up to 7y; (■) children up to 18y; (●) adults. nonevacuated people - (◊)children up to 7y; (Y) children up to 18y; (O) adults.

doses for the residents of the Gomel and Mogilev oblasts. However, it also can be seen in Fig.1 that the radioiodine fallout in Vitebsk (Belarus) and Obninsk (Russia) lasted longer than one or two days; in the future, this protracted period of deposition should be taken into account in the thyroid dose estimation for the residents of those areas.

Differences in lifestyle and dietary habits resulted in different individual thyroid doses even within one settlement and one age group. The obtained individual thyroid dose distributions in general can be described with a lognormal function. Examples of such distributions, which are represented as straights line in a lognormal probability plot, are presented in Fig.2. The lognormal function was shown to describe satisfactorily the distributions of individual thyroid doses for the people from several settlements as well as for the people from the whole administrative raion. Fig.3 shows the lognormal probability

Table 2. Arithmetic mean values of "measured" individual thyroid doses (Class-1 data), calculated for rural residents in some contaminated territories of Gomel and Mogilev oblasts.

Contaminated territories (raions)	Arithmetic mean of Class-1 data and percentage of the measured residents					
	Children up to 7y		Children up to 18y		Adults	
	D, Gy	%	D, Gy	%	D, Gy	%
Bragin*	2.1	57	1.5	56	0.80	71
Bragin**	1.8	55	1.1	63	0.48	91
Hoiniki*	4.7	59	3.1	56	1.6	50
Hoiniki**	1.8	62	1.1	66	0.53	63
Narovlya*	1.6	13	1.0	15	0.45	34
Narovlya**	1.3	37	1.0	38	0.36	57
Vetka	1.6	9.3	1.2	8.5	0.34	2.6
Rechitsa	1.6	17	1.1	15	0.44	12
Loev	0.87	47	0.72	46	0.32	19
Klimovichi	0.37	6.2	0.25	5.3	0.088	4.8
Kostukovichi	0.45	20	0.35	16	0.21	15
Krasnopolye	0.62	13	0.42	19	0.19	17
Slavgorod	0.22	12	0.15	17	0.10	7.4
Chericov	0.54	28	0.34	25	0.13	20

* - the territory of the raion, which had been left by all the residents before May 5, 1986.
** - the non-evacuated territory of the raion.

plot of "measured" individual thyroid doses for the residents in Hoiniki raion, subdivided into groups.

It can be seen in Fig. 3 that children within one group (nonevacuated people or evacuated people) generally received higher thyroid doses than adults, and also that a fraction of small doses is higher for nonevacuated people than for evacuated ones. Arithmetic mean values of "measured" individual thyroid doses (Class-1 data), calculated for rural residents in some contaminated territories of Gomel and Mogilev oblasts are presented in Table 2 . It is important to note that the highest "measured" doses do not exceed 60 Gy.

2. "Passport" individual thyroid doses (data of Class-2 reliability).

"Passport" doses have been calculated for the rural settlements in Gomel and Mogilev oblasts with sufficient number of available Class-1 data (not less than 10 measured residents). On the basis of the available "measured" doses, average thyroid doses have been estimated for each of 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) for the residents in the selected settlements. Also, the thyroid doses to nursing infants fed by mother's milk and the thyroid doses to the fetus can be estimated by multiplying the mother's dose by age-dependent coefficients. The "passport" of the settlement presents the data in the form of a Table consisting of 19 rows and 11 columns. Each row corresponds to one age group while each of the 11 columns corresponds to one level of fresh cow's milk consumed daily by the resident, from 0 L d^{-1} (inhalation intake only) to 4.0 L d^{-1}. Also has been included into the Table the special case when the information on the level of milk-consumption rate is absent. The contribution to the thyroid dose due to ^{131}I intake with leafy vegetables is considered to be small for most individuals and has not been included into the Table in this first stage of dose reconstruction.

At present, over 800 rural settlements in the most contaminated areas in Gomel and Mogilev Oblasts have been provided with "passports". In addition, for about 100 settlements, important dosimetric data such as the arithmetic mean of the individual thyroid doses have been determined. Therefore, about 930 settlements (out of a total number of about 23,500 settlements in Belarus) have been provided with collective characteristics (with different degrees of reliability) of thyroid exposure. Taking into consideration the "passportized" large cities (Minsk, Gomel, Mogilev, and Mozyr) about 2,700,000 residents of Belarus (approximately 27% of the Belarussian population in 1986) are provided with Class-1 or Class-2 data of reliability.

3. "Inferred" individual thyroid doses (data of Class-3 reliability).

The large number of Class-1 data and the availability for many areas in Belarus of measured depositions of radionuclides on the ground [9] provided the opportunity to determine empirical relationships between the average thyroid dose received by people in the rural settlements and the ground-deposition density of radionuclides (radiocesium or radioiodine) in this settlement and in the area around the settlement. Using these relationships, thyroid doses can be inferred for residents of settlements with very few, or no, thyroid measurements. These "inferred" doses (or data of Class-3 reliability) can be estimated for the approximately 7,300,000 Belarussian residents without either "measured" or "passport " doses.

Fig.4 shows, for the settlements in three raions (Hoiniki in Gomel oblast, and Kostukovichi and Krasnopolye , in Mogilev oblast), the variation of the quotient of the arithmetic mean "measured" thyroid dose (D_{mjx}) for the adult population in the settlement (j) to the ^{137}Cs ground-deposition density (q_{Csjx}) as a function of the ^{137}Cs ground-deposition density (q_{Csjx}). Such dependencies can be described satisfactorily with the following expression [10]:

$$D_{jx} = 3.5\times10^{-8}\times q_x(^{131}I) + 1.4\times10^{-8}\times q_{jx}(^{131}I)$$
$$= 3.5\times10^{-8}\times R_x\times q_x(^{137}Cs) + 1.4\times10^{-8}\times R_{jx}\times q_{jx}(^{137}Cs) \qquad (1)$$

where D_{jx} - arithmetic mean thyroid dose for adult population in settlement (j) in area (x) in the absence of any countermeasures in the settlement and for typical lifestyle and dietary habits, in Gy;

$q_x(^{131}I)$, $q_x(^{137}Cs)$ - average ground-deposition density of ^{131}I (^{137}Cs) in area (x), in Bq m^{-2};

$q_{jx}(^{131}I)$, $q_{jx}(^{137}Cs)$ - average ground-deposition density of ^{131}I (^{137}Cs) in the settlement (j) in area (x), in Bq m^{-2};

R_x, R_{jx} - average ratio of the ^{131}I to ^{137}Cs ground-deposition densities in area (x) and in settlement (j) in area (x), respectively.

The numerical coefficients 3.5×10^{-8} and 1.4×10^{-8} Gy m^2 Bq^{-1} have been estimated by the least square method using the data related to the nonevacuated residents of the Hoiniki raion in Gomel oblast, which had been selected as the "reference" territory. To illustrate the adequacy of using equation (1) for estimating the "inferred" thyroid doses, the ratios of "measured" average thyroid dose (D_{mjx}) for adults from the settlements (j) in Bragin raion (nonevacuated residents) in Gomel oblast and in Kostukovichi and Krasnopolye raions in Mogilev oblast, calculated on the basis of "measured" individual doses, to "inferred" average thyroid dose (D_{jx}) for adults in the same settlements (j), calculated according to eq.(1), have been plotted in Fig. 5 against the ^{137}Cs deposition densities in those settlements

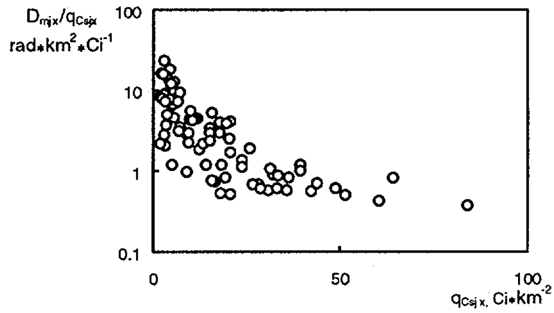

Fig.4. Ratio of arithmetic mean "measured" thyroid dose (D_{mjx}) for the adult population in the settlement (j) to ^{137}Cs ground-deposition density (q_{Csjx}) versus (q_{Csjx}) for the settlements in Hoiniki, Kostukovichi, and Krasnopolye in Belarus.

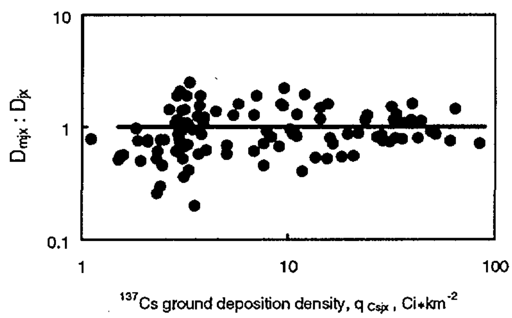

Fig.5. Comparison of "measured" thyroid doses (D_{mjx}) to calculated thyroid doses (D_{jx}) according to the "semiempirical" model.

It can be clearly seen in Fig.5 that the semiempirical model gives reasonable estimates of "inferred" average thyroid dose for all the considered range of ^{137}Cs ground-deposition density.

The procedure of "inferred" thyroid dose assessment on the basis of equation (1) requires information on the ground-deposition density of radiocesium and of radioiodine in the considered settlements and in the area (x) as a whole. That requirement is essential for reconstruction of Class-3 data. Ongoing research may clarify whether equation (1) is generally applicable to all contaminated areas of Belarus and of the other Republics of the former Soviet Union. It is likely that correction coefficients taking into account the role of fuel particles, and parameters such as the standing crop biomass, the fraction of cow's intake from pasture grass, and the date of the beginning of cow's pasture will need to be factored in.

Table 3. Estimates of geometric standard deviation for the parameters used in individual thyroid dose assessment of Class-1, Class-2, and Class-3 data.

Parameter	Geometric standard deviation
Thyroidal ^{131}I content (for Class-1 data)	≤1.3 (Group 1) from 1.3 to 1.7 (Group 2) from 1.7 to 2.2 (Group 3)
Thyroid mass [11]	1.6
Temporal variation of ^{131}I intake	1.3
Daily milk consumption (for each age group)	1.6 ± 0.1
Time-integrated concentration of ^{131}I in milk	2.1 ± 0.3
Uptake of ^{131}I in the thyroid [11]	1.4 - 1.5 (2.0 for newborn)
Distribution of individual thyroid doses for the residents of a given age-group in the settlement	2.7 ± 0.5
Average "passport" dose for the residents of a given age group in the settlement	≤1.5
Average "inferred" dose for the residents of a given age group in the settlement	from 1.5 to 1.8
Class-1 data ("measured" doses)	≤1.7 (Group 1) from 1.7 to 2.0 (Group 2) from 2.0 to 2.5 (Group 3)
Class-2 data ("passport" doses)	from 2.2 to 2.9
Class-3 data ("inferred" doses)	from 2.6 to 3.3

4. Uncertainty of Class-1, Class-2, and Class-3 data.

The current estimates of the main sources of uncertainties as well as of the total uncertainties for Class-1, Class-2, and Class-3 data are presented in Table 3. Future investigations will be devoted to a more thorough evaluation of each parameter uncertainty as well as of the total uncertainty attached to the individual thyroid doses. In particular, a distinction should be made between random and systematic uncertainties, for example for the results of measurement of thyroidal ^{131}I content. The systematic uncertainty of the results of measurement of thyroidal ^{131}I content for the residents of a settlement is transferred in its entirety to the "passport" doses for that settlement, while the random uncertainty decreases as the number of "measured" doses increases. For a number of settlements, the nonrepresentativity of the available Class-1 data, for instance because of the registration of only the highly exposed residents as was the case in Rechitsa raion in Gomel oblast, is a source of systematic uncertainty in the "passport" doses. That source of systematic uncertainty can be removed if information for all other residents is available. As a matter of fact, at the present time, the differences in the uncertainties of Class-2 and Class-3 data result only from the uncertainties in the average thyroidal ^{131}I contents for the adult population. All other sources of uncertainties are taken to be the same.

Table 4. Estimates of the collective thyroid doses for the people of Belarus.

Contaminated territories	Collective thyroid doses for the residents, 10^3 man.Gy		
	Children up to 7 y	Adults	Total
Minsk city	12.2	20.5	39.8
Total in Minsk Oblast (including Minsk city)	*15.0*	*28.2*	*51.7*
Gomel city	22.4	28.3	64.7
Three raions of Gomel Oblast: Bragin, Hoiniki and Narovlya	16.7	37.4	64.2
The other raions of Gomel Oblast	45.4	128.3	197.6
Total in Gomel Oblast	*84.5*	*194.0*	*326.5*
Mogilev city	5.5	11.2	20.9
Five raions of Mogilev Oblast: Chericov, Klimovichi, Kostyukovichi, Krasnopolye, and Slavgorod	8.5	14.8	29.3
The other raions of Mogilev Oblast	9.0	20.2	36.3
Total in Mogilev Oblast	*23.0*	*46.2*	*86.5*
Total in Grodno Oblast	*3.0*	*7.1*	*11.8*
Total in Brest Oblast	*7.3*	*17.6*	*29.0*
Total in Vitebsk Oblast	*1.2*	*2.6*	*4.4*
Total in Republic	*130*	*300*	*510*

5. Collective thyroid doses for the inhabitants of Belarus.

Estimates of collective thyroid doses for the residents of Belarus are presented in Table 4. A large proportion of people were measured in the most heavily contaminated raions of Gomel oblast. The estimates of the collective doses for the populations of those raions have been made on the basis of the available "measured" individual thyroid doses. The same method was used for the urban residents in Minsk, Gomel, and Mogilev cities. A combination of "passport" doses and "inferred" doses, calculated according to equation (1), was used for the raions of Gomel and Mogilev oblasts for which "passport" dose information was incomplete. The collective estimates for the weakly contaminated raions of oblasts other than Gomel and Mogilev were assessed using only equation (1).

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