Chernobyl Accident: Preliminary Estimates of Thyroid Dose Based on Direct Thyroid Measurements Conducted in Belarus

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INTRODUCTION

The April 26, 1986 accident at the Chernobyl nuclear power plant led to radioactive contamination of large territories in many countries. The largest deposition of radiocesiums and radioiodines occurred in parts of Belarus, Ukraine, and Russia. This paper focuses on thyroid doses received by citizens of Belarus at the time of accident. In some areas countermeasures were applied to reduce the population exposure: evacuation and relocation of residents; temporary restriction of the consumption of locally produced foods and distribution of stable iodine pills among residents. In May-June 1986 a large-scale program of in vivo thyroid ^{131}I activity measurements was established in Belarus. More than 200,000 measurements among inhabitants of the most contaminated regions of Belarus were screened at that time. The quality of the measurements was limited by several factors. First of all, the personnel of mobile measurement teams (with the exception of a few individuals) did not have adequate training. Secondly, because sophisticated equipment was not available, simple survey meters with output in exposure or count rate were used. Finally, there were no standard procedures for making thyroid measurements and recording the results. To use the measurement data for dose estimation it was necessary first to estimate all significant systematic and random sources of errors. Additional personal information was also needed. Data on milk and vegetable consumption, duration of residence in contaminated areas, type and time of countermeasures undertaken were obtained through interviews of cohort members (1).

A method for individual thyroid dose estimation, based on the results of direct thyroid measurements and interview data is given here. The method has been used to estimate thyroid doses for Belarusian citizens.

MEASUREMENT OF THE ^{131}I CONTENT IN THYROIDS

The following survey meters were used for large-scale monitoring of the Belarusian population: DP-5, a Geiger-Muller counter as a detector (used for 89% of all measurements), SRP-68-01 (9%) and DRG3-02 (2%), both with NaI(Tl) scintillation detectors. All these meters have analog outputs with 95% confidence intervals of no better than 30% for DP-5 and 10% for the SRP-68-01 and DRG3-02 devices.

Because the thyroid monitoring started after May 5, 1986 (ten days after the accident) it was known that nearly all short-lived radioiodines (^{132}I, ^{133}I, ^{134}I, and ^{135}I) had decayed by the time of the measurements and only ^{131}I was present in thyroids (2).

All results of thyroid measurements can be divided into four groups depending on measurement conditions (Table 1). The most reliable measurements are in groups 1 and 2. Most of the measurements were made in the least desirable environments using the DP-5 instrument.

DYNAMICS OF RADIOIODINE INTAKE BY INDIVIDUALS

The dynamics of the radioiodine intake by individuals can be estimated using information about their residence and food consumption practices in April-May 1986. In 1988, interviews of about 150,000 evacuees and residents of the controlled areas of Gomel and Mogilev Oblasts were conducted. The following personal information was collected: the dates and locations of residence from April 26 through May 31, 1986, the duration of fresh milk consumption, the dates when the cows (goats) began to consume pasture grass, and the dates when potassium-iodide pills were consumed.

Table 1. Characteristics of reliability of the thyroid measurements depending upon the conditions of measurements.

Reliability group	Percentage of measurements	Devices	Locations	Comments
1	3	DRG3-02, SRP-68-01	Hospitals in Minsk and Gomel	Low background. Several measurements. Clothes were removed and patients washed themselves prior to the measurements
2	8	SRP-68-01	Medical offices N28 and N5 in Minsk	Low background. Single measurements of the Minsk inhabitants. Low level of surface contamination.
3	19	DP-5	Hospitals in Gomel and Mogilev, raion clinics, sanatoria, recreation facilities, summer camps	Low background. As a rule, clothes were removed and subjects washed themselves prior to the measurements
4	70	DP-5	At family residences	High background. Presence of surface contamination during the measurements

ASSESSMENT OF THE THYROIDAL 131I CONTENT

The thyroidal ^{131}I content $G(t_m)$ at the time of measurement t_m was calculated using the following formula (3):

$$G(t_m) = k(d,i) \times [P_{th}(t_m,d)-P_b(t_m,d)] = k(d,i) \times P_J(t_m,d) \qquad (1)$$

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

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

$P_b(t_m,d)$ 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”), $\mu R\ h^{-1}$;

$P_J(t_m,d)$ is the component of the reading due to ^{131}I in the thyroid, $\mu R\ h^{-1}$.

There is only one measured quantity in equation (1): $P_{th}(t_m,d)$. It is necessary to estimate the values of $k(d,i)$, and $P_b(t_m)$.

In order to estimate the values of the calibration coefficient k(d,i) for different types of instrument and different measurement geometries, a special investigation was conducted in 1988-1989 in Moscow Clinic N6 with adults who were prescribed ^{131}I. The results of that investigation are shown in Table 2. It is seen from Table 2 that for standard conditions the uncertainty in the calibration coefficient k(d,adult) is lowest for the SRP-68-01 instrument. Two of the nonstandard measurement conditions lead to significant changes in the calibration coefficient for the DP-5 instrument. Age dependency of the values of k(d,i) is taken into account by introduction of an additional multiplicative unitless term with values that range from 0.60 for the newborns to 0.89 for children aged 15 y (4).

Table 2. The values of calibration coefficient k(d,adult) under standard operational conditions of thyroid measurements for all the meters and nonstandard operational conditions for the DP-5 instrument.

Type of device	Operational conditions	Number of measurements	Characteristics of calibration coefficient k(d,i)	
			Geometric mean kBq h mR^{-1}	GSD
SRP-68-01	Standard[a]	110	170	1.23
DRG3-02	Standard[a]	110	270	1.28
DP-5	Standard[a]	110	370	1.30
DP-5	Nonstandard (1) [b]	78	670	1.20
DP-5	Nonstandard (2) [c]	76	930	1.20
DP-5	Nonstandard (3) [d]	73	310	1.29

[a] Standard: the detector was placed in front of the neck under the thyroid. The detectors for the SRP-68-01 and DRG3-02 meters were directed to thyroid with toroidal surface. The DP-5 detector was directed to thyroid with sidelong surface with window closed by moving shield.

[b] Nonstandard (1): the detector was placed in front of the neck rotated with 180^0 relative to its cylindrical axis in comparison with its standard position.

[c] Nonstandard (2): the position of the detector was analogous to nonstandard (1) with an additional shift from the neck as far as about 1.5 cm.

[d] Nonstandard (3): the position of the detector was standard, but the window was not covered by the shield.

It was rather difficult to estimate $P_b(t_m,d)$, as the instruments registered the gross gamma irradiation from all the sources. The background radiation was composed of the following components: environmental radiation at the place of measurement, external radioactive contamination of body surface and clothes, and internal contamination by radionuclides other than ^{131}I that were incorporated into the body. For a substantial fraction of the subjects, two measurements were carried out: one against the thyroid and the other against the liver. In those cases, the measurement against the liver was assumed to represent P_b,. In the absence of a second measurement, the value of Pb was estimated on the basis of experimentally derived relationships. The analysis of the results showed that the contribution of external contamination was about 50%. Internal body contamination was found to be less important and it was necessary to take it into account only for rather late measurements (conducted in June).

ESTIMATION OF THE THYROID DOSE FROM ^{131}I

The thyroid dose, D, resulting from internal exposure to β-γ-rays of ^{131}I can be estimated as follows:

$$D = N \text{ x } (E_e/m) \text{ x } G(t_m) \text{ x } F(t_m) \qquad (2)$$

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

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

m is the mass of the thyroid, in kg;

the numerical values of E_e/m are based on ICRP Publication 56 (5). The values of E_e/m are in the range from 1.6×10^{-12} J kg^{-1} for newborns to 1.9×10^{-11} J kg^{-1} for adults;

$F(t_m)$ is a function describing the processes of ^{131}I intake and elimination from the thyroid, d.

As a first approximation, it was assumed that there were single radioactive ^{131}I fallout events in Gomel and Mogilev Oblasts. According to Makhon'ko et al. (6) these events happened at the following dates:

- April 27, for southern and western raions of Gomel Oblast;
- April 28, for northeastern raions of Gomel Oblast (including Gomel city) and for all of the Mogilev Oblast.

Intake of ^{131}I with locally produced milk is the main pathway for thyroid exposure of the rural population. The results of interviewing were used to determine the value of $F(t_m)$. Three main variants of ^{131}I intake with fresh milk were assumed:

- milk consumption was interrupted on May 3 by children and on May 4 by adults in evacuated villages in three southern raions (Bragin, Hoiniki, and Narovlya) in Gomel Oblast;
- milk consumption was interrupted on May 7 by children and on May 12 by adults in non-evacuated 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.

It was assumed that the urban population had mixed ^{131}I intake (inhalation and ingestion). A large number of thyroid measurements (more than 10,000) made for adult residents of Minsk helped to determine an empirical relationship between the average value of the thyroidal ^{131}I content $G(t_m)$ and the time of measurement t_m for all the Minsk inhabitants. For residents of other cities: Gomel, Mogilev, and Mozyr the thyroid dose was assumed to be equal to the average of two doses (one was calculated assuming only ingestion of ^{131}I with milk and the other dose was calculated assuming only inhalation of ^{131}I).

CONTRIBUTION OF THE SHORT-LIVED RADIOIODINES TO THE THYROID DOSE

The relative contribution, s_s, of short-lived radioiodines to the thyroid dose (expressed as ratios of ^{131}I thyroid doses) can be described as:

$$s_s = \frac{D_{g1}}{D_1} \times \sum_{i=2}^{n} \left(\frac{F_{gi}}{F_{g1}} \times \frac{Q_{gi}}{Q_{g1}} \right) + \frac{D_{h1}}{D_1} \times \sum_{i=2}^{n} \left(\frac{F_{hi}}{F_{h1}} \times \frac{Q_{hi}}{Q_{h1}} \right) \qquad (3)$$

where D_{g1}, D_{h1}, D_1 are internal thyroid doses from ingestion, inhalation, and total intake of ^{131}I, respectively, Gy;

F_{gi}, F_{hi} are age-dependent dose coefficients for ingestion and inhalation intake of radionuclide i, respectively, Gy Bq^{-1}.

Q_{gi}, Q_{hi} are ingestion and inhalation intakes of radionuclide i, respectively, Gy Bq^{-1}.

F_{g1}, F_{h1}, Q_{g1}, Q_{h1} are similarly defined dose coefficients and intakes for ^{131}I.

The first term in the right part of equation (3) describes the contribution due to ingestion of short-lived radioiodines while the second term gives the contribution of inhalation.

The dose coefficient values were taken from publications of the International Commission on Radiological Protection (7, 8, 9).

Regarding the contributions of inhalation and of ingestion to the thyroid dose from ^{131}I, it was assumed that for adult rural inhabitants who had consumed locally produced milk the ratio of D_{g1}/D_{h1} was equal to 20. For urban inhabitants it was assumed that the ingestion and inhalation doses from ^{131}I were approximately the same. In order to calculate the intakes of the short-lived radioiodines and of ^{132}Te, relative to ^{131}I, radioactive decay was taken into account for the short-lived radioiodines and a correction coefficient of 0,7 was applied to ^{132}Te

RESULTS AND DISCUSSION

Individual thyroid doses were estimated and a dosimetry data bank was established for approximately 130,000 Belarusian people. Table 3 presents the geographical distribution of the doses included in the data bank.

It can be seen from Table 3 that about 73% of the dose estimates are for inhabitants of the Gomel Oblast. The doses for residents of three southern raions (Bragin, Hoiniki, and Narovlya) account for about 53% of the total number of doses in the data bank.

Table 3. The data bank of thyroid doses for the Belarusian people.

Territories	Number of persons with dose estimates		
	Children up to 18 y	Adults	Total
	Gomel Oblast		
Three southern raions: Bragin, Hoiniki, and Narovlya	17557	48778	66335
Two raions: Loev and Rechitsa	5257	9299	14556
Three northeastern raions: Buda-Koshelev, Korma, and Vetka	1947	2324	4271
Gomel City	2249	3364	5613
Mozyr City	705	765	1470
Total for Gomel Oblast	*27715*	*64530*	*92245*
	Mogilev Oblast		
Five raions: Chericov, Klimovichi, Kostyukovichi, Krasnopolye, and Slavgorod	4377	8491	12868
Mogilev City	197	910	1107
Total for Mogilev Oblast	*4574*	*9401*	*13975*
	Minsk Oblast		
Minsk City	7211	12830	20041
TOTAL	**39500**	**86761**	**126261**

Figure 1 shows the distribution of the thyroid doses, D_{1I}, for the adult population (N=656) of Pogonnoe village in Hoiniki raion in Gomel Oblast. Figure 1a shows the distribution of thyroid doses and Figure 1b shows the distribution of logarithms of the thyroid doses. It is seen that the distribution of $\ln(D_{1i})$ is close to normal. The distribution of $\ln(D_{1i})$ can be approximated by a normal function with an asymmetry coefficient of 0.10 (standard error 0.10), and an excess coefficient of -0.066 (standard error 0.19). Thus, the lognormal function describes the distribution of thyroid dose reasonably well.

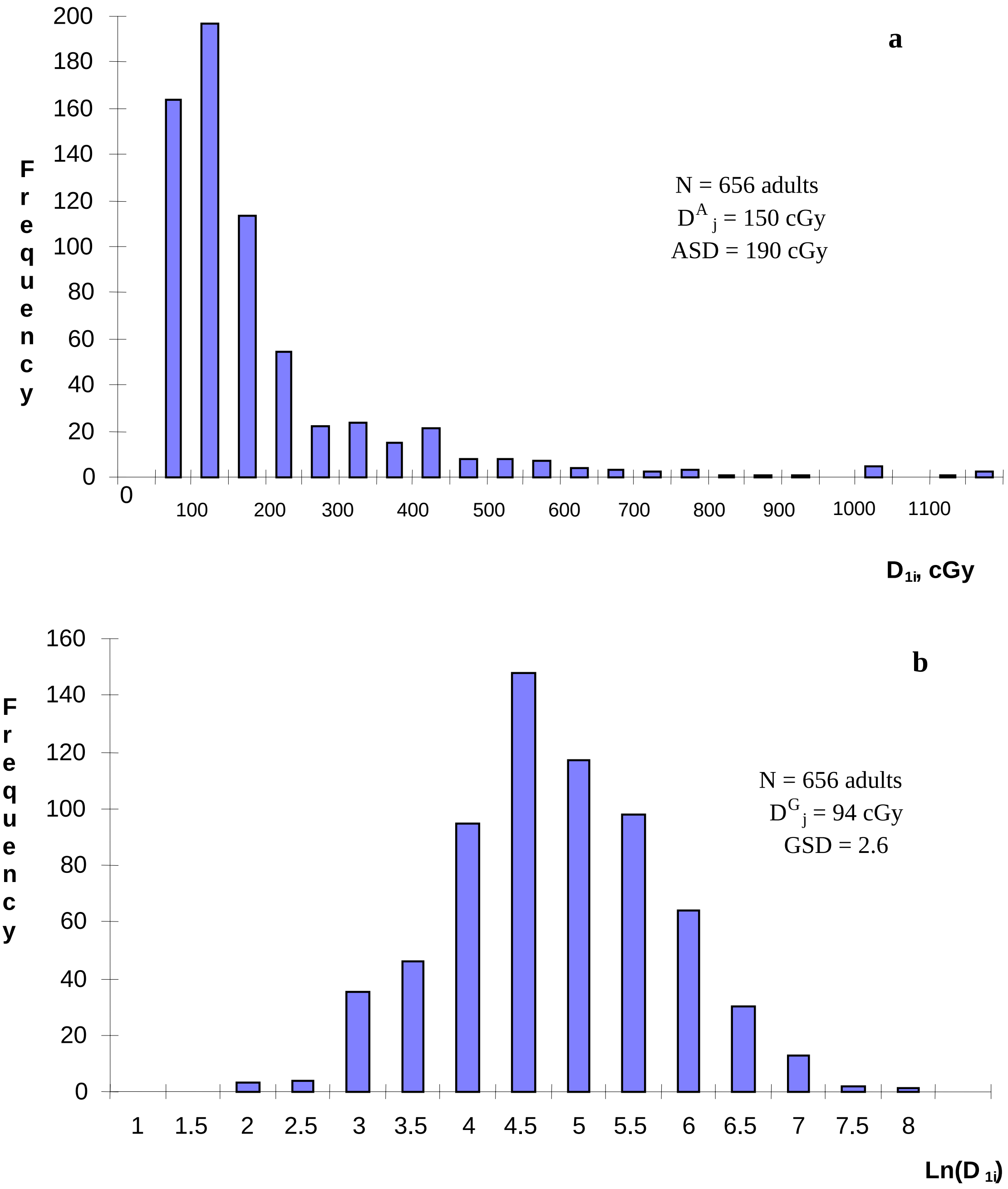

Figure 1. The distributions of individual thyroid dose estimates for the adult population in village Pogonnoe in Hoiniki raion in Gomel Oblast. In plot a, D^A_j is the arithmetic mean of individual dose estimates and ASD is the arithmetic standard deviation. In plot b, D^G_j is the geometric mean of individual dose estimates and GSD is the geometric standard deviation.

The information on median and mean doses for adults and children in some areas of Belarus and children as well as the distribution of the individual thyroid dose estimates are given in Table 4. It is seen that the highest thyroid doses were received by the inhabitants of the evacuated villages in Bragin, Hoiniki, and Narovlya raions. The highest calculated dose was 57 Gy. Thyroid doses for urban populations were significantly lower than those who lived in rural areas.

Table 4. Levels of thyroid dose from radioiodines in some areas of Belarus where direct thyroid measurements were conducted.

Areas	Age-group	Median, Gy	Arithmetic mean, Gy	Percentage of people with doses D_i in the range, Gy: $D_i≤0,3$	$0,3<D_i≤1$	$1<D_i≤3$	$3<D_i≤10$	$D_i>10$
Evacuated villages (before May 5, 1986) in Bragin, Hoiniki, 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, Hoiniki, 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%	-	-	-	-

Preliminary estimates of the contributions of short-lived radioiodines to the thyroid dose, expressed as percentage of the ^{131}I dose, were:

- 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.

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

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