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Questionnaire- and Measurement-Based Individual Thyroid Doses in Ukraine Resulting from the Chornobyl Nuclear Reactor Accident

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The U.S. National Cancer Institute (NCI), in cooperation with the Ministries of Health of Belarus and of Ukraine, is involved in epidemiological studies of thyroid diseases presumably related to the Chornobyl accident, which occurred in Ukraine on 26 April 1986. Within the framework of these studies, individual thyroid absorbed doses, as well as uncertainties, have been estimated for all members of the cohorts (13,215 Ukrainians and 11,918 Belarusians), who were selected from the large group of children aged 0 to 18 whose thyroids were monitored for γ radiation within a few weeks after the accident. Information on the residence history and dietary habits of each cohort member was obtained during personal interviews. The methodology used to estimate the thyroid absorbed doses resulting from intakes of ^{131}I by the Ukrainian cohort subjects is described. The model of thyroid dose estimation is run in two modes: deterministic and stochastic. In the stochastic mode, the model is run 1,000 times for each subject using a Monte Carlo procedure. The geometric means of the individual thyroid absorbed doses obtained in the stochastic mode range from 0.0006 to 42 Gy. The arithmetic and geometric means of these individual thyroid absorbed doses over the entire cohort are 0.68 and 0.23 Gy, respectively. On average, the individual thyroid dose estimates obtained in the deterministic mode are about the same as the geometric mean doses obtained in the stochastic mode, while the arithmetic mean thyroid absorbed doses obtained in the stochastic mode are about 20% higher than those obtained in the deterministic mode. The distributions of the 1000 values of the individual thyroid absorbed dose estimates are found to be approximately lognormal, with geometric standard deviations ranging from 1.6 to 5.0 for most cohort subjects. For the time being, only the thyroid doses resulting from intakes of ^{131}I have been estimated for all subjects. Future work will include the estimation of the contributions to the thyroid doses resulting from external irradiation and from intakes of short-lived (^{133}I and ^{132}Te) and long-lived (^{134}Cs and ^{137}Cs) radionuclides, as well as efforts to reduce the uncertainties.

INTRODUCTION

The accident on 26 April 1986 at the Chornobyl[2] nuclear power plant, located in Ukraine about 10 km south of the border with Belarus, was the most severe ever to have occurred in the nuclear industry. Massive releases of radioactive materials into the atmosphere led to substantial radiation exposures among the populations of Ukraine, Belarus and Russia. These radiation exposures were due initially to ^{131}I and short-lived radionuclides and subsequently to radiocesiums (^{134}Cs and ^{137}Cs) from both external irradiation and the consumption of foods contaminated with these radionuclides (*1*).

Beginning 4 years after the accident, an increase in the number of thyroid cancers was observed among children, in regions of Belarus, Russia and Ukraine (*2–4*), where thyroid absorbed doses[3] had been estimated to be relatively high (*5–7*). In the mid-1990s, NCI conducted a case-control study that concluded that there is a relationship between thyroid dose and cancer in the heavily contaminated areas of Belarus (*8*). There is now little doubt that the increase in the incidence of pediatric thyroid cancer in those areas is related to some extent to radiation exposures resulting from the Chornobyl accident (*1, 9, 10*). The exact nature of the relationship between thyroid dose and thyroid cancer, however, remains to be quantified.

In the early 1990s, NCI entered into official bi-national agreements with the Ministries of Health of Belarus and Ukraine to pursue long-term cohort studies of thyroid diseases among the exposed populations in the two countries (*11*). The studies are outlined in similar research protocols, and designed to provide dose-specific estimates of the risk of thyroid disease after childhood exposure to ^{131}I (*12*). Individual thyroid doses due to intakes of ^{131}I have been es-

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[2] Standard Ukrainian spellings of place names are used in this paper. The most noticeable differences are for the site of the accident and the nation's capital, Kyiv, but the names of other locations also differ from those used in previously published papers.

[3] In this paper, the simpler terms ''thyroid dose'' and ''dose'' also have been used to refer to the radiation absorbed dose in the thyroid.

timated for all cohort subjects—approximately 13,000 in Ukraine and 12,000 in Belarus—after the first round of medical screening, which was carried out between 1998 and 2000 in Belarus and between 1999 and 2001 in Ukraine.

The assessment of the individual thyroid doses from intakes of ^{131}I is based on the results of measurements of γ radiation using detectors placed against the neck. Within a few weeks after the accident, approximately 200,000 of those measurements (called ‘‘direct thyroid measurements’’) were made in Belarus and about 150,000 were performed in Ukraine. All cohort subjects were selected randomly from the large number of children with direct thyroid measurements who were 0 to 18 years old at the time of the accident. For the sake of brevity, only the results for the Ukrainian subjects that were obtained after the first round of medical screening are presented in this paper. Information on the thyroid doses received by the Belarusian subjects and on the results of the clinical examinations of the Ukrainian subjects has been presented elsewhere (*13, 14*). In addition, in a recent publication (*15*), thyroid doses for the entire population of Ukrainian children aged 0 to 18 at the time of the accident have been presented according to a three-level system of thyroid dose estimation:

1. At the first level, individual doses to the thyroid are calculated for all persons with direct thyroid measurements, with a distinction made between two categories: (1) the individuals whose residence histories and dietary habits were obtained by means of personal interviews and (2) the individuals for whom residence history and dietary habits were assumed on the basis of information for the population in the same area of residence at the time of the accident.
2. At the second level of the system of dose estimation, group doses to the thyroid are estimated for the population that resided at the time of the accident in locations (settlements) where direct thyroid measurements were carried out.
3. At the third level of the system of dose estimation, group doses to the thyroid are estimated for the population that resided at the time of the accident in locations where no direct thyroid measurements were carried out.

The degree of precision of the thyroid dose estimates decreases from the first to the third level in the system of dose estimation and is highest for individuals that are considered in this paper, that is, those with a direct thyroid measurement and a personal interview on residence history and dietary habits. These thyroid dose estimates are called *questionnaire-based instrumentally individualized thyroid doses*, *instrumentally individualized thyroid doses*, or *instrumental thyroid doses* (*13, 15*). For the sake of simplicity, they are called *instrumental thyroid doses* in this paper.

Only the intakes of ^{131}I have been considered in these estimates of individual thyroid doses. Thyroid doses resulting from minor pathways, such as external irradiation and intakes of radionuclides other than ^{131}I, have not been estimated on an individual basis. Assessments of those pathways, carried out in the framework of other studies, have shown that, in general, they contribute less than 3% to the total thyroid dose but could be much more important under certain conditions (*16–18*). Plans are being made to include estimates of individual doses from minor pathways when the thyroid dose estimates due to intakes of ^{131}I are re-evaluated after subsequent rounds of screening.

MATERIALS AND METHODS

The assessment of the individual thyroid doses is based on the results of the direct thyroid measurements, which yield estimates of the ^{131}I activities in the thyroids at the time of the measurements. Usually, individuals were measured only once, so that the thyroid dose rate resulting from the ^{131}I activity is inferred for only one time. To calculate the thyroid dose, which is proportional to the time-integrated activity of ^{131}I in the thyroid, the variation with time of the ^{131}I activity had to be assessed. This was done using (1) the results of personal interviews, which were conducted with all cohort members during the first round of screening to obtain information on residence history, dietary habits, and individual actions taken to reduce doses, and (2) an ecological model, which determined the relative rate of intake of ^{131}I, both before and after the measurement, and the variation with time of the ^{131}I activity in the thyroid, taking into account the metabolism of ^{131}I in the body and its possible modification by the intake of prophylactic stable iodine. A detailed description of the ecological model is provided in Appendix 1.

The combination of the results of the direct thyroid measurements, personal interviews, and ecological model yields individual estimates of instrumental thyroid dose, which are intended to be used for epidemiological purposes. A detailed description of the manner in which the instrumental thyroid doses are calculated is provided in Appendix 2. In addition, *ecological thyroid doses*, which make use of only the results of the personal interviews and of the ecological model and ignore the results of the direct thyroid measurements, are estimated for comparison purposes. For the purposes of this paper, the instrumental thyroid doses have been calculated in a deterministic and in a stochastic mode, while the ecological doses have been calculated only in a deterministic mode. Figure 1 shows the data and the procedures used to estimate the individual thyroid doses. Those procedures, which are discussed below, are classified into four categories: (1) description and analysis of the direct thyroid measurements, (2) the conduct of the personal interviews, (3) the description of the ecological model, and (4) the estimation of the individual thyroid doses.

Direct Thyroid Measurements

The direct thyroid measurement entailed placing a γ-radiation detector against the neck. The detector reading was either in terms of exposure rate (μR h^{-1} or mR h^{-1}) or, for energy-selective devices, in count rate (counts per minute, cpm) from an energy window centered on the 364 keV γ-ray energy peak of ^{131}I. The distribution with time of the number of direct thyroid measurements made in Ukraine in May–June 1986 is shown in Fig. 2; almost all of the direct thyroid measurements were made between 10 and 60 days after the accident, that is, after the short-lived ^{133}I (half-life: 21 h) and ^{132}Te (half-life: 3.2 days) had substantially decayed and before ^{131}I (half-life: 8.0 days) decayed to negligible levels.

Background count or exposure rate was subtracted from the direct measurement of the gross thyroid count or exposure rate to yield the net thyroid count or exposure rate. The background consists basically of three components: (1) surface contamination of the skin, hair and clothes; (2) internal contamination of the body by radionuclides other than ^{131}I; and (3) environmental contamination.

Up to 20 May 1986, the background value was usually determined on the basis of measurements made against the forearm, liver and head. More

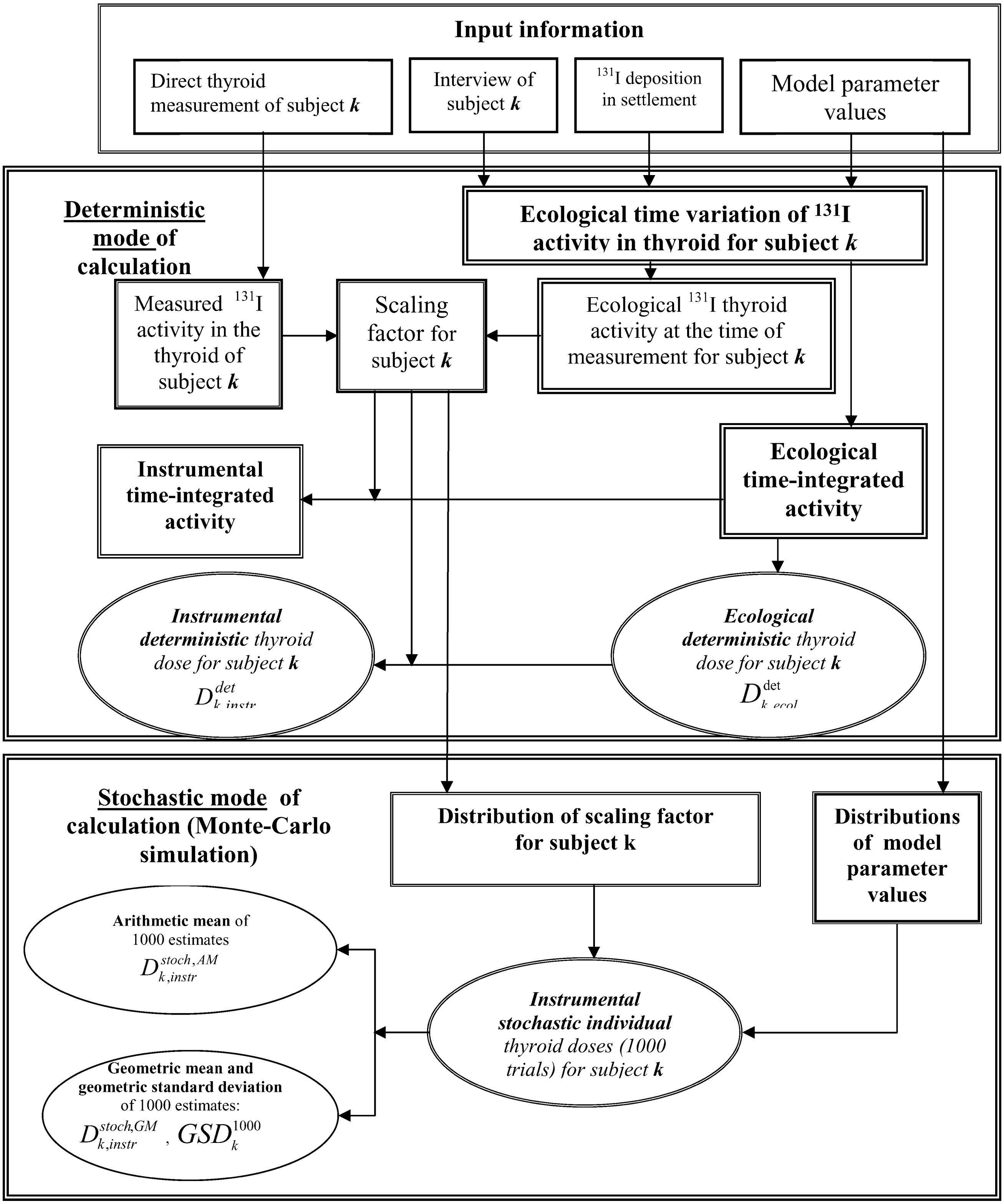

FIG. 1. Input information and procedures used for the estimation of the instrumental and ecological doses in deterministic and stochastic modes.

than 5,000 individuals (including about 500 cohort members) were monitored in that manner. Background was found to range from 30 to 140% of the signal measured against the thyroid. The analysis of those measurements showed that most of the background was due to the surface contamination of the skin. Further measurements, made after the neck was washed thoroughly with alcohol solution, led to the conclusion that the internal contamination of the body by radionuclides other than ^{131}I (mainly radiocesiums) represented only 5 to 9% of the signal (^{131}I activity in the thyroid) in May 1986 and no more than 20% of the signal at the end of June.

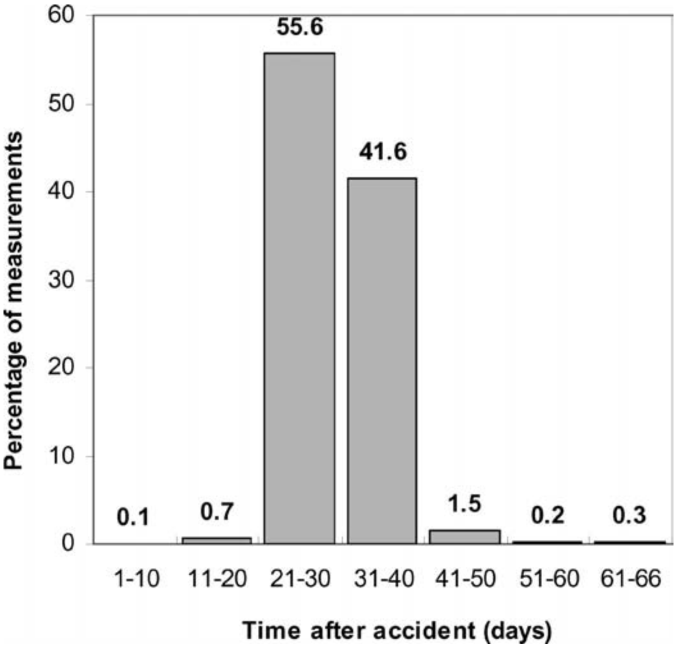

FIG. 2. Temporal distribution of the number of direct thyroid measurements made in May–June 1986 in Ukraine.

After 20 May 1986, all measurements against the thyroid were made after the neck was thoroughly cleaned, and the background consisted of an indoor radiation measurement in the absence of the individual to be measured. The background value was then corrected for the partial shielding of background by the human body. When exposure-rate meters were used, the background was observed to vary from 5 to 500 μR h^{-1} depending on location and time after the accident, the average value being about 40 μR h^{-1}. When spectrometers were used, the background values ranged from 20 to 4,000 counts min^{-1}.

The ^{131}I activity present in the thyroid at the time of measurement, t_m, was derived from the net exposure or count rate using the calibration coefficient for the detector. The value of the calibration coefficient depends on the device that was used, the geometry of measurement, and the size of the thyroid. In addition, careful measurements and detailed calculations were carried out to estimate the uncertainties associated with the estimated values of the calibration coefficients (*19*). The results of an investigation of the reliability and quality of the measurements as well as of the quantification of the uncertainties due to the variability of the age-dependent thyroid mass, the thickness of the overlying tissue, and the position of the detector relative to the thyroid are given elsewhere (*20*).

Personal Interviews

Personal interviews were conducted with all cohort members to obtain information on (1) their whereabouts during the first 2 months after the accident (until the end of June 1986) when substantial concentrations of ^{131}I were present in the environment; (2) their consumption rates of milk, milk products and leafy vegetables during the same period; (3) the origins of the foodstuffs that they consumed; and (4) whether, and if so, when, they took stable iodine for protection purposes. Cohort members were invited to the interview with their parents, and a self-administered questionnaire was sent to them prior to the interview to help them prepare for it. Cohort members who were less than 10 years old at the time of the accident were not expected to be able to respond correctly to all of the questions. Therefore, it was planned that they would be interviewed with one of their parents, preferably their mother. A stationary team, based in Kyiv city, and four mobile teams were responsible for the conduct of the interviews, which were carried out within the framework of the medical screening. Most of the interviews were completed within 30 to 40 min. The stationary team and the mobile teams conducted 3,802 and 9,441 interviews, respectively; 28 interviewees were later found not to be members of the cohort.

Because many invited parents did not participate in the interviews and some subjects did not have a good recollection of their whereabouts and dietary habits during the first 2 months after the accident, accurate numerical responses to all questions were not provided during some interviews. For example, the subject would indicate that he or she changed residence during the first few days of May 1986 but could not be more specific. Also, the recollection of the consumption rates of milk and leafy vegetables was often vague. In addition, information on the consumption rates of milk products was not requested during the interviews. For these reasons, detailed protocols were developed to make point estimates of parameter values for the individual thyroid dose calculations in the deterministic mode and to estimate appropriate uncertainties to be used for calculations of individual thyroid doses in the stochastic mode. For example, when no reliable information on the consumption rates of milk or leafy vegetables was available for the subject, average values obtained for the cohort subjects with reliable information for the same age group were used (see Tables A1.2 and A1.3 in Appendix 1).

Ecological Model

The ecological model addresses all steps from radioactive fallout to thyroid irradiation, through the contamination of foodstuffs and inhalation, using available information on the behavior of ^{131}I in the environment and on the use that the cohort members made of the environment. As illustrated in Fig. 1, the ecological model (1) uses as input the contents of databases on the activities of ^{131}I that were deposited on the ground, (2) takes into account the set of parameters that characterize the human exposure pathways leading to inhalation and to the consumption of cow's milk and leafy vegetables, and (3) takes into consideration information obtained during personal interviews of the cohort members on residence history, dietary habits and iodine prophylaxis.

Measurements of ^{131}I deposition per unit area of ground (hereafter called ground deposition densities and expressed in kBq m^{-2}), and of the dynamics of that deposition, are available for only a few settlements in Ukraine (*21*). A model of atmospheric transport was developed to estimate the values of ^{131}I ground deposition densities for any location where the cohort members resided during the first 2 months after the Chornobyl accident (*22*). The calculated results of ^{131}I ground deposition densities were reasonably consistent with the few available measurements of ^{131}I.

The set of parameters that characterize the human exposure pathways of inhalation and consumption of cow's milk and leafy vegetables was derived from the abundant literature devoted to the environmental behavior of ^{131}I (*23–30*). The parameter values and their distributions are given in Appendix 1.

The ecological model has the following end points: (1) a calculated activity of ^{131}I in the thyroid at the time of measurement based on the ecological model and the human metabolic model of ^{131}I, (2) a calculated time-integrated activity of ^{131}I in the thyroid, and (3) a dose corresponding to individual ecological thyroid dose.

Estimation of Individual Thyroid Doses

Four estimates of individual thyroid doses have been calculated for every subject, *k*:

1. The deterministic instrumental ($D^{det}_{k,instr}$) and deterministic ecological ($D^{det}_{k,ecol}$) thyroid doses, which are obtained when the model is run using central estimates of the parameter values.
2. The geometric and arithmetic means of the instrumental thyroid dose ($D^{stoch,GM}_{k,instr}$ and $D^{stoch,AM}_{k,instr}$, respectively) obtained when the model is run in a stochastic mode, in which probability distributions are assigned to most of the parameter values.

For each cohort member, the thyroidal content of ^{131}I at the time of

TABLE 1
Central Estimates and Distributions of Some of the Parameter Values (*13*)

Parameter				Distribution	
Description	Symbol	Unit	Central estimate	Type	Parameters
Daily deposition of ^{131}I	$P(t,s)$	kBq m^{-2} day^{-1}	Measured, interpolated, or calculated	Lognormal	GSD[a] = 1.6–2
Interception coefficient	b_1	unitless	0.5	Triangular	Range: 0.3–0.7
Transfer coefficient to cow's milk for ^{131}I	f_m	day $liter^{-1}$	4×10^{-3}	Lognormal	GSD = 2.1
Daily intake of grass by cow	I_p	kg day^{-1}	40	Uniform	Range: 30–50
Consumption rate of private cow's milk	r_3	liter day^{-1}	Age-dependent	Lognormal	GSD = 1.4–2.6
Removal rate of ^{131}I from the thyroid	λ_{th}	day^{-1}	Age-dependent	Normal	CV[b] = 5%
Measured activity of ^{131}I in the thyroid	M_{res}	kBq	Device-dependent, age-dependent, etc.	Lognormal	GSD = 1.1–1.4[c]
Thyroid mass	m_{th}	g	Age-dependent	Lognormal	GSD = 1.6

[a] Geometric standard deviation.
[b] Coefficient of variation.
[c] Although the uncertainties related to the measured ^{131}I activity in the thyroid were relatively low (GSD = 1.1–1.4) for most cohort subjects, they were much higher, with a maximum GSD of 12, when the signal recorded by the thyroid was close to background. In those cases, however, the instrumental doses were low.

measurement that was calculated by means of the ecological model was compared with the result of the direct thyroid measurement. The ratio of the ecological and instrumental values is the scaling factor, which was calculated for all cohort members. The individual values of time-integrated activity of ^{131}I in the thyroid and of thyroid dose were derived from the direct thyroid measurements (for the instrumental dose) or from the calculated ^{131}I activity in the thyroid at the time of the direct thyroid measurement (for the ecological dose) using in both cases the ecological model run in deterministic mode. Therefore, the ratio of the deterministic ecological and instrumental doses for a given individual is equal to the scaling factor obtained for that individual.

In the stochastic mode, distributions of individual instrumental doses for every cohort member were calculated with a Monte Carlo procedure. For that purpose, probability distributions were assigned to most of the parameter values. Those parameters can be classified into five categories, namely those related to (1) the derivation of the ^{131}I thyroid content at the time of the direct thyroid measurement, (2) the transfer of ^{131}I in the environment, (3) the answers provided during the personal interviews, (4) the reduction in the ^{131}I concentrations in foodstuffs between production and consumption, and (5) human metabolism of ^{131}I. The types and characteristics of the distributions (central estimates and dispersion) of some of the parameters that were considered are shown in Table 1; a more detailed description is provided in Appendix 1. It was assumed in the Monte Carlo calculations that all parameters were independent. In each trial, a value of the instrumental dose was estimated using randomly selected values of the parameters weighted according to their probability distributions. One thousand values of the instrumental dose were calculated in that manner for every cohort member. Finally, the arithmetic ($D_{k,instr}^{stoch,AM}$) and geometric ($D_{k,instr}^{stoch,GM}$) means of the 1,000 values of the instrumental dose as well as the geometric standard deviation of their distribution (GSD_k^{1000}) were estimated for every cohort member.

TABLE 2
Distribution of Subjects According to Age

Age (years)	Number of males	Number of females	Total number
0	367	366	733
1	490	469	959
2	489	492	981
3	478	484	962
4	409	392	801
5	402	358	760
6	385	349	734
7	398	382	780
8	426	386	812
9	435	437	872
10	439	412	851
11	431	385	816
12	436	392	828
13	388	386	774
14	347	340	687
15	191	226	417
16	138	142	280
17	73	81	154
18	13	1	14
Total	6735	6480	13,215

RESULTS AND DISCUSSION

Individual thyroid doses were estimated for 13,215 Ukrainians who underwent the first round of medical screening in the framework of the epidemiological study conducted by the Ministry of Health of Ukraine, in cooperation with NCI. Each person had a direct thyroid measurement within a few weeks after the accident, was 0 to 18 years old at the time of the direct thyroid measurement,[4] and was interviewed to obtain information on his or her residence history and dietary habits. The age and gender distribution of the cohort subjects is presented in Table 2. For each year of age, the numbers of boys and girls are approximately equal. The numbers of subjects are about the

[4] Because the measurements were made within a few weeks after the accident, the age at the time of measurement was considered to be the same as the age at the time of the accident.

TABLE 3
Main Characteristics of the Distributions of the Instrumental and Ecological Thyroid Dose Estimates for the Ukrainian Subjects

Averages for the entire cohort[c]	Individual estimations for subject k						
	Deterministic mode		Stochastic mode (instrumental dose)[a,b]				Deterministic to stochastic mode ratio
	$D^{det}_{k,instr}$	$D^{det}_{k,ecol}$	$D^{stoch,GM}_{k,instr}$	GSD^{1000}_{k}	$D^{stoch,AM}_{k,instr}$	$D^{stoch,AM}_{k,instr}/D^{stoch,GM}_{k,instr}$	$D^{det}_{k,instr}/D^{stoch,GM}_{k,instr}$
	Gy		Gy	unitless	Gy	—	—
GM^{coh}	0.23	0.34	0.23	1.8	0.27	1.2	0.99
GSD^{coh}	4.4	3.2	4.4	1.1	4.3	1.1	1.0
AM^{coh}	0.68	0.62	0.68	1.8	0.79	1.2	0.99
97.5 percentile	4.3	2.7	4.3	2.5	4.9	1.5	1.1
2.5 percentile	0.013	0.028	0.013	1.6	0.017	1.1	0.91

[a] $D^{stoch,GM}_{k,instr} = \exp(\sum_{n=1}^{1000} \ln D_{k,instr,n}/1000)$ is the geometric mean of the results of 1000 trials in a Monte Carlo procedure used for the stochastic estimation of the individual thyroid dose for subject k; $D_{k,instr,n}$ is the dose estimate obtained for subject k in trial n.

[b] $GSD^{1000}_{k} = \exp\sqrt{\sum_{n=1}^{1000} (\ln D_{k,instr,n} - \ln D^{stoch,GM}_{k,instr})^2/1000}$ is the geometric standard deviation of 1000 trials in a Monte Carlo procedure used for the stochastic estimation of the individual thyroid dose for subject k.

[c] GM^{coh}, GSD^{coh} and AM^{coh} are the geometric mean, geometric standard deviation and arithmetic mean of the corresponding distributions of individual estimates for the entire cohort.

same for each year of age between 0 and 14 and decrease substantially for the ages of 15 to 18 years. Because of the relative paucity of older children, the median age of the cohort members was 7 years and about two-thirds of the cohort members were less than 10 years old at the time of the accident.

The overall characteristics of the estimates, for the entire cohort, of instrumental dose, calculated in deterministic and stochastic modes, and of ecological dose calculated in deterministic mode are shown in Table 3:

1. The geometric mean values (GM^{coh}) of the estimates of individual instrumental doses for the entire cohort are very similar both for the stochastic and the deterministic modes: 0.23, 0.23 and 0.27 Gy for the GM^{coh} of $D^{det}_{k,instr}$, $D^{stoch,GM}_{k,instr}$ and $D^{stoch,AM}_{k,instr}$, respectively.
2. The geometric mean over the entire cohort of the estimates of individual ecological dose $D^{det}_{k,ecol}$ is somewhat higher (0.34 Gy).

Most of the discussion that follows will be focused on the estimates of instrumental dose obtained in stochastic mode, since those are the values that are to be used in the epidemiological analysis:

1. Ninety-five percent of individual instrumental doses $D^{stoch,GM}_{k,instr}$ are in the interval from 0.003 to 14.4 Gy, depending mainly on the age of the subject and on his or her place of residence at the time of the accident.
2. The distribution of doses $D^{stoch,GM}_{k,instr}$ in the cohort is very close to lognormal, with a geometric standard deviation of 4.4; the arithmetic mean of that distribution is 0.68 Gy (to be compared to a geometric mean of 0.23 Gy).
3. The 1,000 values of thyroid dose obtained in stochastic mode for each subject are found to be approximately lognormally distributed. The geometric standard deviations of their distributions (GSD^{1000}_{k}) are in the interval from 1.6 to 4.7 for 95% of the cohort subjects; however, for most subjects the values of GSD^{1000}_{k} are less than 2, so that the individual arithmetic mean doses $D^{stoch,AM}_{k,instr}$ are, on average, only about 20% higher than the geometric mean doses $D^{stoch,GM}_{k,instr}$.
4. For all individuals, the deterministic instrumental dose, $D^{det}_{k,instr}$, is very close to the geometric mean of the stochastic instrumental dose, $D^{stoch,GM}_{k,instr}$.

Two of the important factors that influence the thyroid dose are (1) the age of the subject, because, for a given intake of ^{131}I, the thyroid dose of a young child is higher than that of an older child whose thyroid is larger; and (2) the residence of the subject at the time of the accident, as the fallout of ^{131}I, and consequently the contamination of milk and other foodstuffs, varied substantially from one location to another.

Table 4 shows that, as expected, the geometric means of the individual instrumental thyroid doses ($D^{det}_{k,instr}$, $D^{stoch,GM}_{k,instr}$ and $D^{stoch,AM}_{k,instr}$) are found to decrease as a function of the age of the cohort members. The doses, either deterministic or stochastic, received by infants are greater by a factor of about 7 than those of 18-year-old teenagers. The geometric mean value of the scaling factor appears to be independent of the age of the subject. There is, however, a very large variability in the values of the thyroid doses and of the scaling factor at the individual level. This variability is shown in more detail in Table 5 for the doses $D^{stoch,GM}_{k,instr}$. In all age groups, there are individuals with thyroid dose estimates less than 0.02 Gy and greater than 1 Gy. The highest values are obtained for the lowest age groups, while the lowest values are observed for the oldest children.

Most of the subjects resided less than 150 km away from the reactor at the time of the accident (Fig. 3). Those from

TABLE 4
Variation of the Deterministic ($D^{det}_{k,instr}$) and Stochastic ($D^{stoch,GM}_{k,instr}$, $D^{stoch,AM}_{k,instr}$) Estimates of Instrumental Thyroid Dose According to the Age of the Cohort Members at the Time of the Accident

	Deterministic mode						Stochastic mode					
	$D^{det}_{k,instr}$ (Gy)			Scaling factor (unitless)			$D^{stoch,GM}_{k,instr}$ (Gy)			$D^{stoch,AM}_{k,instr}$ (Gy)		
Age (years)	Geometric mean[a]	Minimum	Maximum	Geometric mean[a]	Minimum	Maximum	Geometric mean[a]	Minimum	Maximum	Geometric mean[a]	Minimum	Maximum
0	0.62	0.003	32	0.8	0.004	460	0.63	0.003	31	0.77	0.014	36
1	0.49	0.011	28	1.3	0.007	97	0.50	0.013	28	0.59	0.018	32
2	0.43	0.006	43	1.3	0.007	403	0.44	0.006	42	0.52	0.012	48
3	0.36	0.001	25	1.4	0.004	460	0.37	0.001	25	0.44	0.011	28
4	0.32	0.006	24	1.4	0.003	130	0.33	0.006	24	0.39	0.013	33
5	0.27	0.001	15	1.4	0.001	560	0.27	0.001	15	0.32	0.008	16
6	0.23	0.002	15	1.5	0.007	340	0.24	0.002	15	0.28	0.007	17
7	0.20	0.003	12	1.7	<0.001	510	0.20	0.002	11	0.24	0.007	13
8	0.17	0.003	13	1.8	0.013	110	0.18	0.003	14	0.21	0.007	16
9	0.17	0.003	8.2	1.7	0.034	250	0.17	0.003	7.9	0.20	0.005	9.0
10	0.15	0.001	9.4	1.7	0.008	670	0.15	0.001	9.2	0.18	0.004	10
11	0.14	0.003	9.0	1.7	0.012	83	0.15	0.003	8.9	0.17	0.004	10
12	0.14	0.002	10	1.6	0.004	260	0.14	0.002	9.9	0.16	0.003	11
13	0.14	0.001	7.2	1.5	0.014	300	0.14	0.001	7.3	0.16	0.003	8.3
14	0.14	0.001	9.1	1.4	0.012	260	0.14	0.001	8.9	0.17	0.002	10
15	0.14	0.001	7.9	1.6	0.027	250	0.14	0.001	8.1	0.16	0.002	9.3
16	0.12	0.001	8.4	1.7	0.021	74	0.12	0.001	8.2	0.14	0.002	9.3
17	0.09	0.001	3.7	2.0	0.042	87	0.09	0.001	3.7	0.11	0.002	4.3
18	0.09	0.002	1.7	1.0	0.046	21	0.10	0.002	1.6	0.12	0.003	1.9

[a] Geometric mean of the distribution of individual estimates for all members of the age group.

the Chornobyl raion[5] resided between 10 and 43 km from the reactor, while those from the Polis'ke raion resided between 16 and 60 km away from the reactor. As shown in Table 6, the location at the time of the accident has a large influence on the average thyroid dose received by its residents. The geographical distribution of the thyroid dose, averaged over doses $D^{stoch,GM}_{k,instr}$ obtained for the cohort members in each of the eight raions of interest and in Kyiv city, is such that the highest average doses, exceeding 1.2 Gy, are found in Narodychi raion, while the lowest doses (0.09 Gy or less) are obtained in Ivankiv and Kozelets' raions. There does not seem to be a clear relationship of the average thyroid dose to the raion average level of ^{131}I deposition, which is given in Table 6. Other factors, such as evacuation, the age distribution of the cohort members in the different raions, the origin of milk available for consumption, and the amount of milk consumed, also affect the dose estimates.

The overall distribution of thyroid doses $D^{stoch,GM}_{k,instr}$ of the Ukrainian subjects is presented in Fig. 4. The analysis of that distribution shows that:

1. According to the Jarque-Bera test (*31*), the shape of the dose distribution for the entire cohort is lognormal, with a geometric mean of 0.23 Gy and a geometric standard deviation of 4.4.
2. Ninety percent of the cohort members received doses between 0.02 and 2.7 Gy.
3. Geometric mean thyroid doses exceeding 20 Gy were estimated for 15 subjects younger than 5 years old; they include 12 residents of the most contaminated settlements of Narodychi raion (seven being from villages Novoyer Sharno and Nozdrischer in Christinovskiy selsovet[6] where the ^{131}I deposition density was greater than 28,000 kBq m^{-2}), two evacuees and one person from Polis'ke raion.
4. Geometric mean thyroid doses less than 0.001 Gy were estimated for six subjects.

The distribution of the uncertainties in the individual thyroid dose estimates, expressed as GSD^{1000}_k, is shown in Fig. 5. The parameters that account for most of the uncertainty are the thyroid mass and those related to the determination of the content of ^{131}I in the thyroid at the time of the direct thyroid measurement. The values of GSD^{1000}_k vary from one individual to another and range from 1.6 to more than 10. The highest values of GSD^{1000}_k are estimated for very low individual doses $D^{stoch,GM}_{k,instr}$, when the signal recorded by the detector is less than 10% higher than background; the values of GSD^{1000}_k decrease as the dose $D^{stoch,GM}_{k,instr}$ increases (Table 7). The average GSD^{1000}_k for all subjects is 1.8 (Table 7).

The geometric mean of the scaling factor is close to 1.5

[5] Raion is an administrative unit within an oblast. Usually there are 10 to 20 raions in an oblast. The raion is comparable to a county in the United States, while the oblast is comparable to a state.

[6] A selsovet is an area within a raion that consists of a group of villages.

TABLE 5
Distribution of the Individual Thyroid Dose Estimates $D^{stoch,GM}_{k,instr}$ for the Subjects According to Age

Age (years)	Number of subjects	Percentage[a] of subjects with thyroid dose $D^{stoch,GM}_{k,instr}$ (Gy) in interval								
		<0.02	0.02–0.05	0.05–0.1	0.1–0.2	0.2–1	1–5	5–10	10–20	≥20
0	733	1.1	1.9	4.6	11	41	33	3.5	1.6	1.1
1	959	0.8	2.1	7.4	13	48	24	3.2	1.0	0.2
2	981	1.8	4.0	7.4	17	42	23	3.0	1.4	0.3
3	962	0.7	3.3	10	19	46	19	1.9	0.5	0.1
4	801	1.1	5.7	13	17	43	19	1.5	0.6	0.1
5	760	1.7	6.2	14	20	41	16	0.8	0.1	0.0
6	734	2.9	9.1	17	19	37	13	1.4	0.7	0.0
7	780	2.4	12	16	22	37	11	0.6	0.1	0.0
8	812	4.4	13	18	21	33	11	0.5	0.1	0.0
9	872	4.7	13	16	22	34	9.0	0.3	0.0	0.0
10	851	5.5	16	19	18	30	10	0.5	0.0	0.0
11	816	8.7	15	17	20	29	9.2	1.0	0.0	0.0
12	828	8.1	17	18	21	27	8.9	1.0	0.0	0.0
13	774	8.8	16	17	18	30	9.4	0.5	0.0	0.0
14	687	8.0	18	18	16	29	9.9	1.0	0.0	0.0
15	417	8.9	18	16	16	29	11	0.7	0.0	0.0
16	280	16	16	17	17	21	11	1.4	0.0	0.0
17	154	20	19	16	10	23	11	0.0	0.0	0.0
18	14	21	14	7.0	14	36	7.1	0.0	0.0	0.0
0–18	13,215	4.6	10	14	18	36	15	1.4	0.4	0.1

[a] The sums of the percentages for a given age are not equal to 100% because of rounding.

for the Ukrainian cohort (Fig. 6). However, individual values may be greater than 10 or lower than 0.1 for a substantial part of the cohort. On the whole, it can be observed that as the dose $D^{stoch,GM}_{k,instr}$ decreases, the scaling factor increases (Table 7). The highest scaling factors are associated with low doses (less than 0.1 Gy) whereas scaling factors less than 1 were estimated for the highest doses D^{GM}_{instr}. As a rule, values of scaling factor greater than 10 are obtained when the signal recorded by the detector is less than 10% higher than background. On the other hand, scaling factors much lower than one are usually obtained when individuals respond that they did not consume any contaminated foodstuffs, yet the measured exposure rate near their thyroid is substantial.

FUTURE WORK

Work is in progress to reduce the uncertainties attached to the thyroid dose estimates resulting from intakes of ^{131}I. The relatively large uncertainties that have been found for low instrumental thyroid dose estimates indicate that the results of the direct thyroid measurements must be analyzed more carefully and, in particular, that the various components of the background need to be taken into consideration. For example, it seems to be important to take into account the influence of the content of ^{137}Cs in the body on the response of the radiation detector, especially when the direct thyroid measurements were performed more than 1 month after the accident.

The variation of the scaling factor as a function of the instrumental thyroid dose points to the need for a re-evaluation of the central estimates and uncertainties of the parameters used in the ecological and metabolism models, so that the averages of the individual scaling factors become close to one for all instrumental dose intervals.

A substantial effort also will be made to investigate the uncertainties attached to the responses provided by the cohort members during the personal interviews.

At present only the thyroid doses resulting from intakes of ^{131}I have been estimated for all subjects. Future work will also include the estimation of the contributions to the thyroid doses resulting from external irradiation and from intakes of short-lived (^{133}I and ^{132}Te) and long-lived (^{134}Cs and ^{137}Cs) radionuclides.

CONCLUSIONS

For the first time, a large number of individual thyroid doses, and their uncertainties, resulting from the large releases of ^{131}I that occurred during the Chornobyl accident, have been estimated in the framework of an epidemiological study of thyroid diseases conducted by the National Cancer Institute in collaboration with the Ministries of Health of Belarus and Ukraine. As far as possible, the same methodology of thyroid dose reconstruction was used for the subjects originating from the two countries that are considered. Only the results obtained for the Ukrainian subjects have been presented in this paper.

The 13,215 Ukrainian subjects, who were selected from the large group of children whose thyroids were monitored for γ radiation within a few weeks after the accident, provided personal information on their residence history and

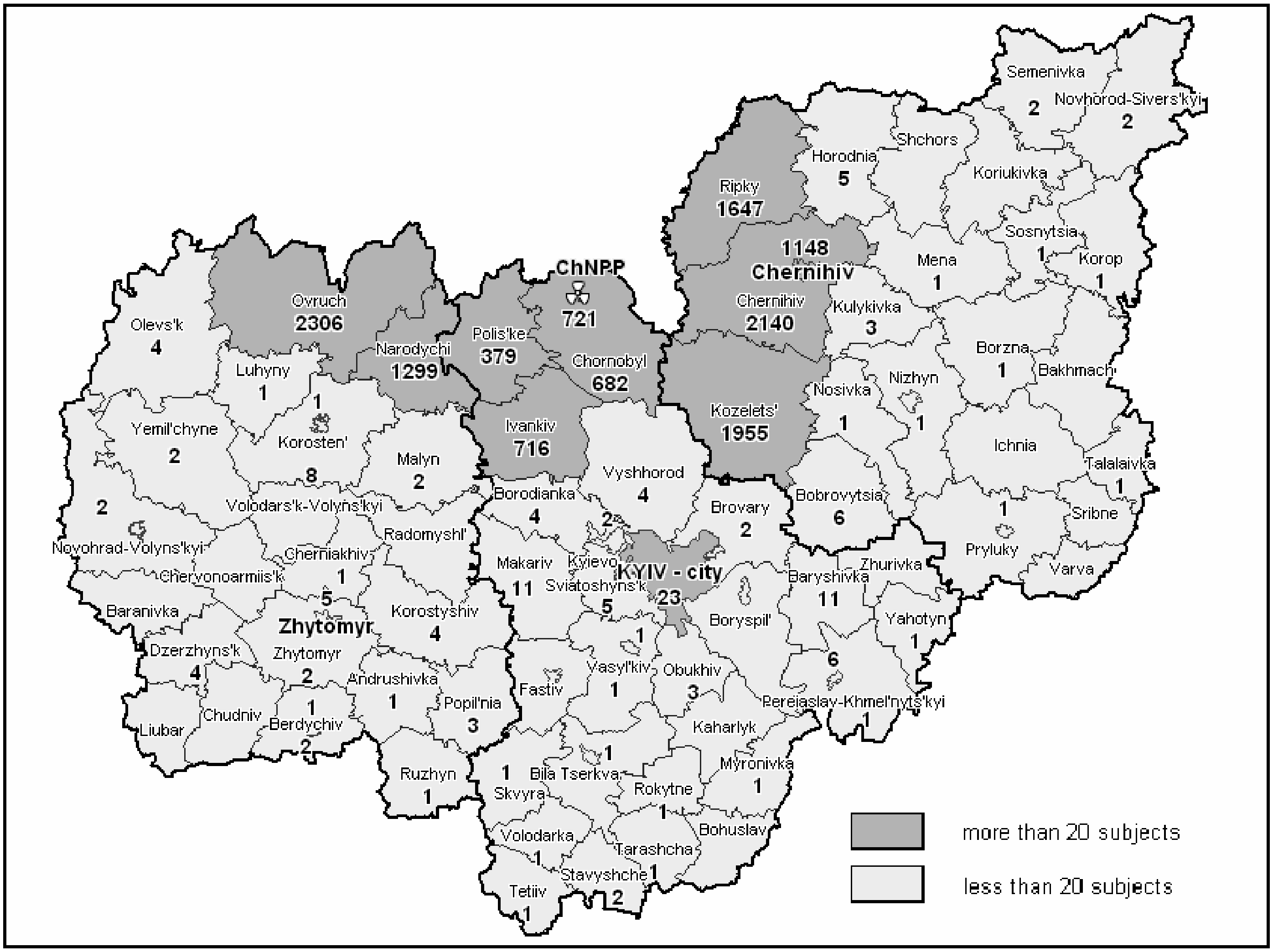

FIG. 3. Distribution of the number of Ukrainian cohort members according to residence at the time of the accident. Only the northern part of the country is shown on this map. An additional 198 subjects resided in other parts of the country.

TABLE 6
Instrumental Thyroid Doses $D_{k,\,instr}^{stoch,GM}$ for Ukrainian Subjects Who Resided in the Most Contaminated Raions of Kyiv, Zhytomyr and Chernihiv Oblasts, in Pripiat' town, and in Chernihiv and Kyiv Cities at the Time of the Accident

			$D_{k,instr}^{stoch,GM}$, Gy			
Oblast and raion	Number of settlements	^{131}I deposition (kBq m^{-2})	Number of subjects	Geometric mean	Minimum	Maximum
Kyiv oblast						
Polis'ke	46	18,000	379	0.36	0.011	19
Chornobyl	47	14,000	682	0.19	0.001	8.6
Ivankiv	56	1400	716	0.09	0.003	5.8
Zhytomyr oblast						
Narodychy	58	5500	1299	1.26	0.009	42
Ovruch	114	2000	2306	0.36	0.002	14
Chernihiv oblast						
Kozelets'	94	340	1955	0.09	0.001	4.5
Ripky	100	420	1647	0.16	0.001	15
Chernihiv	101	400	2140	0.24	0.002	15
Chernihiv-city		260	1148	0.13	0.003	8.2
Kyiv-city		470	23	0.18	0.002	18
Pripiat' town			721	0.37	0.004	25

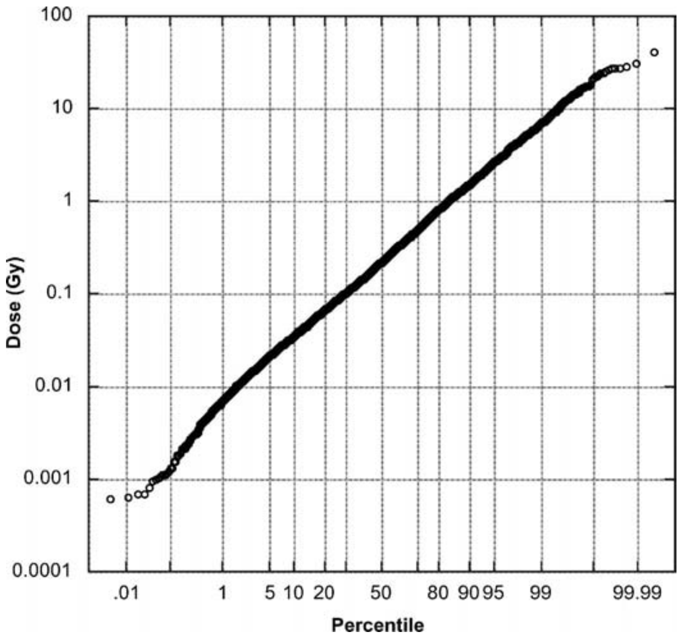

FIG. 4. Distribution of the instrumental thyroid doses $D_{k,instr}^{stoch,GM}$ of the Ukrainian cohort members. The individual doses are represented by open circles; in a lognormal distribution, the individual doses would be distributed along a straight line.

dietary habits during interviews. The model of thyroid dose estimation was run in two modes: deterministic and stochastic. In the stochastic mode, the model was run 1,000 times for each subject using a Monte Carlo procedure. The geometric and arithmetic means of the 1,000 dose outputs were estimated for each individual. The geometric means of the thyroid doses obtained in the stochastic mode for each individual range from 0.0006 to 42 Gy. The arithmetic

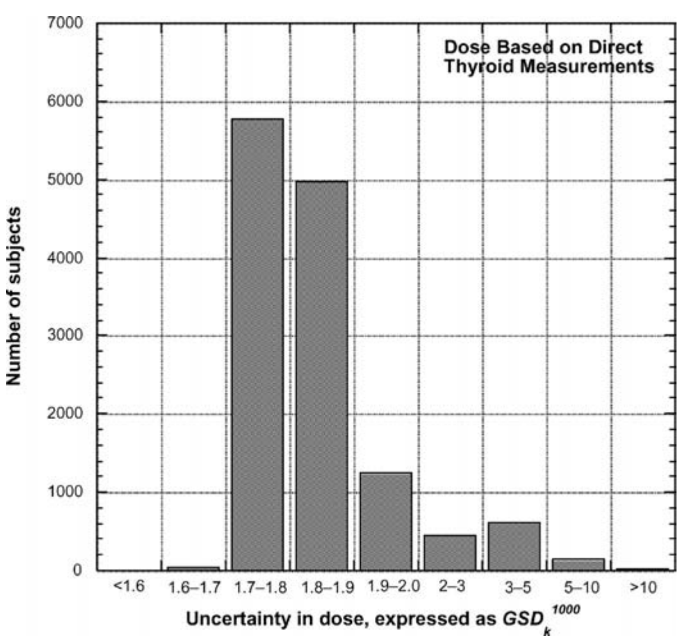

FIG. 5. Distribution of the geometric standard deviation (GSD_k^{1000}) of the instrumental thyroid dose for the Ukrainian cohort subjects.

TABLE 7
Variation of the Uncertainty (Expressed as GSD_k^{1000}) and of the Mean Scaling Factor According to the Value of the Geometric Mean Instrumental Thyroid Dose Estimate, $D_{k,\,instr}^{stoch,GM}$

$D_{k,\,instr}^{stoch,GM}$ (Gy)	Number of subjects	Average GSD_k^{1000} for group	Mean scaling factor
<0.005	81	3.6	108
0.005–0.01	138	2.4	34
0.01–0.1	3630	1.8	7.8
0.1–1	7139	1.7	2.2
1–10	2158	1.7	0.59
10–20	54	1.7	0.14
>20	15	1.7	0.093
All	13,215	1.8	1.5

and geometric means of these individual doses obtained in stochastic mode for the entire cohort were found to be 0.68 and 0.23 Gy, respectively. On average, the individual thyroid dose estimates obtained in the deterministic mode are about the same as the geometric mean doses obtained in the stochastic mode, while the arithmetic mean doses obtained in the stochastic mode are about 20% higher than those calculated in the deterministic mode.

The distributions of the 1000 values of the individual thyroid absorbed dose estimates are found to be approximately lognormal. For dose estimates based on thyroid activity measurements, the individual geometric standard deviations associated with these distributions vary from one individual to another. For 95% of them, the geometric standard deviations are in the range from 1.6 to 4.7, the median being 1.8. The parameters that account for most of the uncertainty are the thyroid mass and those related to the determination of the content of ^{131}I in the thyroid at the time of the direct thyroid measurement.

Although these estimates of thyroid dose and of their uncertainties will be used at this stage of the epidemiological study, all aspects of the dose estimation process are being re-evaluated, so more accurate and precise thyroid

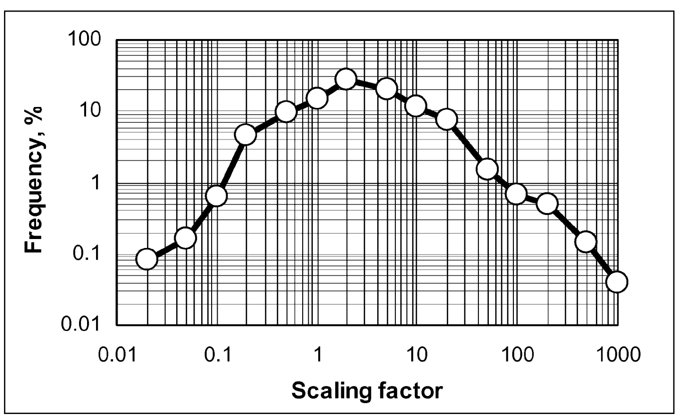

FIG. 6. Distribution of the scaling factors for the subjects of the Ukrainian cohort.

dose estimates resulting from ^{131}I intakes could be derived in a few years. In addition, the revised thyroid dose estimates will include the contributions resulting from the intake of short-lived radioiodines (^{133}I and ^{135}I) and radiotelluriums (^{131m}Te and ^{132}Te), from the intake of the long-lived radiocesiums (^{134}Cs and ^{137}Cs), and from external irradiation arising from the deposition of radionuclides on the ground and other materials,

APPENDIX 1

Description of the Ecological Model used to Estimate Individual Thyroid Doses Resulting from Intakes of ^{131}I

The ecological model used to estimate the individual thyroid doses resulting from intakes of ^{131}I takes into account the following modes of exposure: (1) inhalation of ground-level contaminated air; (2) ingestion of cow's milk, either from personal cows or from shops; (3) ingestion of cow's milk products; (4) ingestion of leafy vegetables; and (5) if appropriate, ingestion of goat's milk or of mother's milk. Minor pathways, such as the absorption of ^{131}I through skin, or licking hands contaminated with ^{131}I, have not been included in the dose estimation process.

Most of the parameter values and their uncertainties were assigned on the basis of a literature review (*23–30*). Other values, specific for Ukraine, are based on expert judgment.

The description of the ecological model follows the logical sequence:

1. Accidental release of ^{131}I, atmospheric transport, and deposition of ^{131}I on the ground.
2. Environmental concentrations of ^{131}I (ground-level air, pasture grass, soil, leafy vegetables. milk and milk products).
3. Intake of ^{131}I by the people.
4. Uptake of ^{131}I by the thyroid.
5. Thyroid content of ^{131}I.
6. Thyroid dose due to ^{131}I intake.

Rate of ^{131}I Deposition on the Ground [$P(t, s)$ in kBq m^{-2} day^{-1}]

Measured values of ^{131}I deposition density are available for a few locations only. For most locations, a model of atmospheric transport is used to estimate the daily values of ^{131}I deposition on the ground (soil and grass), which could occur on several days. These values are denoted as $P(t, s)$, where t is the time after the accident (26 April 1986) in days and s represents the location (in terms of latitude and longitude) of the settlement (all locations where the subject resided between 26 April and 30 June 1986 are considered).

It is assumed that the estimates of daily deposition density of ^{131}I are log normally distributed with a geometric standard deviation (GSD) varying from 1.6 to 2.0 depending on the region that is considered.

Concentration of ^{131}I in Ground-Level Air [$C(t, s)$ in kBq m^{-3}]

It is calculated as $C(t, s) = [P(t, s)]/[V_g(t, s)]$, where $V_g(t, s)$ is the dry deposition velocity on soil and grass (m day^{-1}). Based on available meteorological data, it is assumed that fallout in Northern Ukraine was due only to dry deposition; thus deposition with rain is not taken into account. The dry deposition velocity, $V_g(t, s)$, is assumed to be lognormally distributed with a geometric mean (GM) of 600 m day^{-1} and a GSD of 1.6.

Concentration of ^{131}I in Pasture Grass [$y_1(t, s)$ in kBq kg^{-1}]

It is described by the following equation:

$$\frac{dy_1(t, s)}{dt} = -\lambda_g \cdot y_1(t, s) + b_1 \cdot \frac{P(t, s)}{Y_g}, \qquad \text{(A1.1)}$$

where λ_g is the effective removal rate of ^{131}I from pasture grass (day^{-1}). Its values are assumed to have a triangular distribution with a mode of 0.15, a lower bound of 0.13, and an upper bound of 0.17 day^{-1}. Y_g is the yield of pasture grass on day of maximum fallout [kg (fresh weight) m^{-2}]. Its values are assumed to have a triangular distribution with a mode of 0.7, a lower bound of 0.42, and an upper bound of 0.98 kg (fresh weight) m^{-2}. b_1 is the fraction of the deposited activity initially retained by pasture grass (unitless). Its values are assumed to have a triangular distribution with a mode of 0.5, a lower bound of 0.3, and an upper bound of 0.7.

Concentration of ^{131}I in Soil [$y_2(t, s)$ in kBq kg^{-1}]

It is described by the following equation:

$$\frac{dy_2(t, s)}{dt} = -\lambda_r \cdot y_2(t, s) + (1 - b_1) \cdot \frac{P(t, s)}{Y_{soil}}, \qquad \text{(A1.2)}$$

where λ_r is the radioactive decay constant of ^{131}I (0.0862 day^{-1}), b_1 is the fraction of the deposited activity initially retained by pasture grass, as discussed above, and Y_{soil} is the mass of contaminated soil per unit area of ground (kg m^{-2}). Assuming that only the upper 0.15 mm of soil (H_{soil}) is contaminated and that the soil density of that superficial layer is 1000 kg m^{-3}, Y_{soil} is found to be equal to 0.15 kg m^{-2}. The values of Y_{soil} are assumed to have a triangular distribution with a mode of 0.15, a lower bound of 0.05, and an upper bound of 0.45 kg m^{-2}. It is important to note that the value of H_{soil} is not measured; it is based on the assumption that the contribution of the soil intake by cows to the ^{131}I concentration in milk from private cows is 6% of that from the intake of pasture grass.

Concentration of ^{131}I in Leafy Vegetables [$yc_1(t, s)$ in kBq kg^{-1}]

The concentration of ^{131}I in leafy vegetables is assumed to be the same as in pasture grass at the time of harvesting. It is also assumed that the leafy vegetables that are consumed are of local origin, both for rural and for urban citizens. Such an assumption is very rough for urban population, but there is no reliable information on sources of early leafy vegetables sold in Ukrainian cities in 1986. The ^{131}I concentration at the time of consumption, $yc_1(t, s)$, is described by the following equation:

$$yc_1(t, s) = y_1(t - TC_1, s) \cdot CF_1 \cdot e^{-\lambda_r \cdot TC_1}, \qquad \text{(A1.3)}$$

where the delay, TC_1, between the harvesting of leafy vegetables and their consumption is taken to be equal to 1 day for urban citizens. The values of TC_1 for urban citizens are assumed to have a triangular distribution with a mode of 1 day, a lower bound of 0.5 day, and an upper bound of 1.5 days. For rural citizens, the delay TC_1 is assumed to be negligible; a culinary factor, CF_1, of 0.8 is applied due to removal of outer leaves and/or to washing. The culinary factor, CF_1, is assumed to be distributed uniformly in the range from 0.6 to 1.0, which means that all values between 0.6 and 1.0 are considered to have the same probability to occur.

Concentration of ^{131}I in Milk from Private Cows [$y_3(t, s)$ in kBq liter^{-1}]

It is described by the following equation:

$$\frac{dy_3(t, s)}{dt} = -\lambda_m \cdot y_3(t, s) + b_3 \cdot y_1(t, s) + b_4 \cdot y_2(t, s), \qquad \text{(A1.4)}$$

where λ_m is the effective rate of decrease of ^{131}I in milk (central value: 1.1 day^{-1}); $\lambda_m = \lambda_r + \lambda_{bm}$, where λ_{bm} is the rate of biological transfer of iodine into milk. The values of λ_{bm} are assumed to have a triangular distribution with a mode of 1.0 day^{-1}, a lower bound of 0.7 day^{-1}, and an upper bound of 1.4 day^{-1}. b_3 is the grass-to-cow milk transfer rate (kg liter^{-1} day^{-1}). It is calculated as

$$b_3 = I_p \cdot f_m \cdot \lambda_{bm}, \qquad \text{(A1.5)}$$

where I_p is the daily intake of pasture grass by cow, taken to be 40 kg day^{-1} (uniform distribution: 30–50 kg day^{-1}), and f_m is the transfer coefficient of cow's intake to milk for ^{131}I, taken to have a central value of 4×10^{-3} day liter^{-1}. The values of f_m are assumed to be lognormally distributed with a geometric mean of 4×10^{-3} day liter^{-1} and a GSD of 2.1; b_4 is the soil-to-cow milk transfer rate (kg liter^{-1} day^{-1}). It is calculated as:

$$b_4 = I_{soil} \cdot f_m \cdot \lambda_{bm}, \tag{A1.6}$$

where I_{soil} is the daily intake of soil by cow, taken to have a central value of 0.5 kg day^{-1}. The values of I_{soil} are assumed to have a triangular distribution with a mode of 0.5 kg day^{-1}, a lower bound of 0.2 kg day^{-1}, and an upper bound of 0.8 kg day^{-1};

It is assumed that there is a delay, TC_3, of 0.25 day between the collection of milk from private cows and its consumption. The ^{131}I concentration in consumed milk from private cows, $yc_3(t, s)$, is calculated as

$$yc_3(t, s) = y_3(t - TC_3, s) \cdot e^{-\lambda_r \cdot TC_3}. \tag{A1.7}$$

Concentration of ^{131}I in Other Types of Milk and in Milk Products

1. Cow's milk from shops

It is assumed that the cow's milk sold in shops is of local origin. This assumption is reasonable for small towns. For big cities, there is no reliable information on milk sources, so the assumption is only a rough approximation.

On the basis of this assumption, a similar methodology is used for the estimation of the ^{131}I concentrations in cow's milk from shops and in cow's milk from private cows. There are only two differences: (1) The estimated ^{131}I concentrations in milk are not allowed to exceed the permissible level, PL, which was set at 3 700 Bq liter^{-1} on 6 May 1986; and (2) there is a delay, TC_4, of 1.5 day between the collection of milk and its consumption. The values of TC_4 are assumed to be distributed uniformly in the range from 1 to 2 days.

Taking into account the above considerations, the concentration of ^{131}I in cow's milk sold in shops, $yc_4(t, s)$ is estimated as

$$yc_4(t, s) = \min\{PL(t); y_3(t - TC_4, s) \cdot e^{-\lambda_r \cdot TC_4}\}, \quad \text{with}$$

$$PL(t) = \begin{cases} \infty, & t < \text{days (before 6 May 1986)} \\ 3.7 \text{ kBq/liter}, & t \geq \text{days (on or after 6 May 1986)} \end{cases} \tag{A1.8}$$

2. Cow's milk products

The concentration of ^{131}I in milk products from private cow's milk and for dairy products from store milk is derived from the concentration of ^{131}I in fresh milk from private cows, with a culinary factor, CF_5, of 0.62 and a delay factor, TC_5, of 2 days applied to that concentration.

The ^{131}I concentration in consumed milk products, $yc_5(t, s)$, is calculated as

$$yc_5(t, s) = y_3(t - TC_5, s) \cdot CF_5 \cdot e^{-\lambda_r \cdot TC_5}, \tag{A1.9}$$

where the central estimate of TC_5 is 2 days (uniform distribution between 1 and 3 days) and the central estimate of CF_5 is 0.62 (uniform distribution between 0.4 and 0.9).

3. Goat's milk

It is assumed that goats eat 4 kg day^{-1} of pasture grass and that their transfer coefficient from feed to milk is 0.2 day liter^{-1}. It is therefore estimated that the ^{131}I concentrations in goat's milk, $yc_6(t, s)$, are $R_g = 5$ times greater than the concentrations in cow's milk from personal cows:

$$yc_6(t, s) = R_g yc_3(t, s). \tag{A1.10}$$

It is assumed that the distribution of R_g is uniform within the range from 2 to 10.

4. Mother's milk

It is assumed that lactating mothers consume 0.8 liter of cow's milk per day and have a diet-to-milk transfer coefficient of 0.37 day liter^{-1}. Therefore, it is assumed that the ^{131}I concentrations in mother's milk, $yc_7(t, s)$, are $R_m = 0.3$ times the concentrations in cow's milk from personal cows:

TABLE A1.1
Values of Age-Dependent Ventilation Rate[a], Thyroid Mass[b], and Effective Rate of Removal of ^{131}I from the Thyroid[c]

Age, years	Ventilation rate, r_1 m^3 day^{-1}	Thyroid mass, m_{th}, g	Effective rate of removal of ^{131}I from the thyroid, λ_{th}, day^{-1}
0	2.9	1.3	0.13
1	5.6	1.8	0.12
2	6.5	2.2	0.12
3	7.4	2.6	0.11
4	8.3	3.0	0.11
5	9.3	3.4	0.11
6	10	4.3	0.10
7	11	5.2	0.10
8	13	6.1	0.10
9	14	7.0	0.097
10	15	7.9	0.096
11	16	8.9	0.096
12	17	9.7	0.096
13	18	11	0.095
14	20	11	0.095
15	20	12	0.095
16	21	13	0.095
17	21	14	0.094
18	22	15	0.094

[a] The values of the ventilation rate r_1 for newborn and 1, 5, 10 and 15 years old are taken from ICRP Publication 66 (*32*). The values between those ages are obtained by linear interpolation.

[b] The values of the thyroid mass m_{th} for newborn and 1, 5, 10 and 15 years old are taken from ICRP Publication 89 (*33*). The ICRP Publication 89 value for adults (20 g) is assumed to correspond to age 25.

[c] The values of the effective rate of removal of ^{131}I from the thyroid λ_{th} are derived from ICRP Publication 56 (*34*).

$$yc_7(t, s) = R_m yc_3(t, s) \quad \text{when mother drank milk from personal cows;} \tag{A1.11}$$

$$yc_7(t, s) = R_m yc_4(t, s) \quad \text{when mother drank milk from shops.} \tag{A1.12}$$

It is assumed that the distribution of R_m is uniform within the range from 0.2 to 0.4.

Daily Intake of ^{131}I by the Cohort Members [Q(t,k) in kBq day^{-1}]

The daily intake of ^{131}I by the cohort members, $Q(t, k)$, has two components: inhalation and ingestion:

$$Q(t, k) = Q_{inh}(t, k) + Q_{ing}(t, k), \tag{A1.13}$$

where $Q_{inh}(t, k)$ is the daily intake by inhalation and $Q_{ing}(t, k)$ is the daily intake by ingestion.

The calculation of the daily intake by inhalation takes into account the fact that the cohort member may have changed his or her settlement of residence, s, during the 2 months after the accident:

$$Q_{inh}(t, k) = \sum_{s=1}^{N_s} I(t, s, k) \cdot r_1(k) \cdot C(t, s), \tag{A1.14}$$

where N_s is the number of settlements of residence of subject k in the period from April 26 to July 1, 1986, and $I(t, s, k)$ has the following values:

$$I(t, s, k) = \begin{cases} 1 & \text{when subject } k \text{ at time } t \text{ was in settlement } s \\ 0 & \text{when the subject } k \text{ at time } t \text{ was not in settlement } s. \end{cases}$$

$r_1(k)$ is the breathing rate of the subject (m^3 day^{-1}). The central values of $r_1(k)$ as a function of age are taken from Table A1.1. Distribution: log-

TABLE A1.2
Default Values of the Mean Consumption Rate of Leafy Vegetables (kg day^{-1})

	Residents of rural settlements		Residents of urban settlements	
Age (years)	Males	Females	Males	Females
0	0.012	0.0097	0.0091	0.010
1–4	0.017	0.015	0.015	0.012
5–9	0.021	0.018	0.018	0.015
10–14	0.024	0.019	0.018	0.016
15–18	0.027	0.019	0.019	0.015

TABLE A1.3
Default Values of the Mean Consumption Rate of Cow's Milk (liter day^{-1})

	Residents of rural settlements		Residents of urban settlements	
Age (years)	Male	Female	Male	Female
0	0.6	0.58	0.72	0.57
1–4	0.45	0.39	0.43	0.37
5–9	0.53	0.35	0.41	0.3
10–14	0.64	0.37	0.42	0.27
15–18	0.66	0.39	0.48	0.3

normal with geometric means as given in Table A1.1 and a GSD of 1.4 for any age.

In a similar way, the daily intake by ingestion is calculated as

$$Q_{ing}(t, k) = \left[\sum_{s=1}^{N_s} I(t, s, k)\cdot\sum_{j=2}^{p} r_j(t, k)\cdot yc_j(t, s)\right], \quad \text{(A1.15)}$$

where j is the index of the type of ingested foodstuffs for the various types of foodstuffs that are considered in the calculations (leafy vegetables, milk and milk products). p is the number of foodstuffs; $r_2(t, k)$ is the consumption rate of leafy vegetables by the subject (kg day^{-1}). To the extent possible, the values of $r_2(t, k)$ are taken from the questionnaires. When the subject was not able to provide information on his or her consumption rate of leafy vegetables, a default value, taken from Table A1.2, was used. The consumption rate of leafy vegetables, $r_2(t, k)$, is assumed to be lognormally distributed with a GSD of 1.4. $r_3(t, k)$ is the consumption rate of cow's milk from private cows by the subject until July 1, 1986 (liter day^{-1}). To the extent possible, the values of $r_3(t, k)$ are taken from the questionnaires. When the subject was not able to provide information on his or her rate of consumption of cow's milk from private cows, a default value, taken from Table A1.3, was used. The consumption rate for cow's milk from private cows, $r_3(t, k)$, is assumed to be lognormally distributed with a GSD of 1.4. $r_4(t, k)$ is the consumption rate of cow's milk from shops by the subject until July 1, 1986 (liter day^{-1}). To the extent possible, the values of $r_4(t, i)$ are taken from the questionnaires. When the subject was not able to provide information on his or her rate of consumption of cow's milk from shops, a default value, taken from Table A1.3, was used. The consumption rate for cow's milk from shops, $r_4(t, k)$, is assumed to be lognormally distributed with a GSD of 1.4. $r_5(t, k)$ is the consumption rate by the subject of milk products (kg day^{-1}). Information on the consumption rate of milk products was not requested during the personal interviews in Ukraine; therefore, the results of the questionnaire applied to the Belarusian cohort members, which included queries on the consumption rate of milk products, were used. The consumption rate of milk products, $r_5(t, k)$, is assumed to be lognormally distributed. Values of geometric mean and of GSD are shown in Table A1.4. $r_6(t, k)$ is the consumption rate of goat's milk by the subject (liter day^{-1}).

Values of the goat's milk consumption rate are taken from the questionnaires. When the subject was not able to provide information on his or her consumption rate of goat's milk, it was assumed that he or she did not consume any goat's milk. The consumption rate of goat's milk, $r_6(t, k)$, is assumed to be lognormally distributed with a GSD of 1.4. $r_7(t, k)$ is the consumption rate of mother's milk (liter day^{-1}) by subjects who were infants at the time of the accident. It is taken to be equal to 0.8 liter day^{-1}. The consumption rate of mother's milk by infant subjects, $r_7(t, k)$, is assumed to be lognormally distributed with a GSD of 1.4.

Daily Uptake of ^{131}I by the Thyroid [F(t, k) in kBq day^{-1}]

The daily uptake, $F(t, k)$, of ^{131}I by the thyroid of subject k is derived from the daily intakes by inhalation, $Q_{inh}(t, k)$, and by ingestion, $Q_{ing}(t, k)$:

$$F(t, k) = w_{th}[w_{inh}\cdot Q_{inh}(t, k) + w_{ing}\cdot Q_{ing}(t, k)], \quad \text{(A1.16)}$$

where w_{th} is the fractional uptake of ^{131}I by thyroid from blood. Distribution: triangular with values of minimum, mode, and maximum equal to 0.2, 0.3, and 0.4, respectively. w_{inh} is the fraction of inhaled ^{131}I activity that is transferred to blood. Distribution: triangular with values of minimum, mode, and maximum equal to 0.5, 0.66, and 0.82, respectively. $w_{ing} = 1$ is the fraction of ingested ^{131}I activity that is transferred to blood. Distribution: no uncertainty.

For the subjects who undertook prophylaxis (stable iodine consumption with pills or solutions), it is assumed that, after intake of stable iodine for prophylactic reasons, the uptake of ^{131}I by the thyroid, w_{th}, is modified by a correction factor, $CF_{KI}(t)$, which varies with time after intake of stable iodine. Therefore, the uptake of ^{131}I by the thyroid becomes $w_{th}CF_{KI}(t)$. The values of $CF_{KI}(t)$ are derived from experiments on human volunteers (*35*) and are in agreement with the values obtained by other researchers (*36*). They are listed in Table A1.5.

Content of ^{131}I in the Thyroid [$y_4(t,k)$ in kBq]

The activity of ^{131}I in the thyroid of subject, k, at time, t, is described by the following equation:

$$\frac{dy_4(t, k)}{dt} = F(t, k) - \lambda_{th}(k)\cdot y_4(t, k), \quad \text{(A1.17)}$$

where $\lambda_{th}(k)$ is the age-dependent rate of ^{131}I removal from the thyroid (day^{-1}). Values are given in Table A1.1. Distribution: normal with a coefficient of variation of 5%.

Ecological Time-Integrated Activity of ^{131}I in the Thyroid [EA(k) in kBq day]

The ecological time-integrated activity of ^{131}I in the thyroid is calculated as

$$EA(k) = \int_0^T y_4(t, k)\, dt, \quad \text{(A1.18)}$$

TABLE A1.4
Central Estimates and Distributions of Consumption Rate of Milk Products, Expressed as Milk Equivalent[a]

Age (years)	GM (kg day^{-1})	GSD
0–1	0.02	2.8
1–2	0.08	2.5
2–7	0.08	2.3
7–12	0.15	2.3
12–17	0.16	2.5
17–18	0.18	2.5

[a] Derived from the information for Belarusian children.

TABLE A1.5
Values of the Correction Factor, $CF_{KI}(t)$, of the Uptake of ^{131}I by the Thyroid after Intake of Stable Iodine for Prophylactic Reasons

Time relative to the intake of KI pill, days	Values of correction factor, $CF_{KI}(t)$, of the uptake of ^{131}I by the thyroid
−1	1
0	0.2
1	0.23
2	0.48
3	0.64
4	0.76
5	0.84
6	0.89
7	0.92
8	0.95
9	1

where $T = 64$ days is the end of the period over which the activity of ^{131}I in the thyroid of the subject is integrated (from 26 April to 30 June 1986). This period was used in the questionnaire for queries on residence history and dietary habits. At the end of June 1986, the ^{131}I activity in the thyroids of the subjects had decreased to very low levels. Changing the value of T from 64 days to infinity would result in trivial increases in the thyroid dose estimates.

Ecological Thyroid Dose ($D^{det}_{k,ecol}$ in mGy)

The ecological thyroid dose of subject, k, is calculated as

$$D^{det}_{k,ecol} = \frac{K_u \cdot E_{th}}{m_{th}(k)} \cdot EA(k), \qquad \text{(A1.19)}$$

where $m_{th}(k)$ is the age-dependent mass of the thyroid (g). Values are taken from Table A1.1. Distribution: log-normal with GSD = 1.6.

E_{th} is the mean energy absorbed in the thyroid per decay of ^{131}I in the thyroid (MeV/decay). Distribution: triangular with a mode of 0.22, a minimum of 0.2, and a maximum of 0.23. The value of E_{th} depends on the degree of absorption within the thyroid of the β particles emitted during the decay of ^{131}I. K_u is a unit conversion factor equal to 13.82 (Bq/kBq) (g/kg) (J/MeV) (s/day) (mGy/Gy). Only the deterministic values of the ecological thyroid doses have been calculated. The parameter values used for those calculations are those designated as central estimates, geometric means, modes values, or averages throughout this Appendix.

APPENDIX 2

Description of the Instrumental Model used to Estimate Individual Thyroid Doses Resulting from Intakes of ^{131}I

Measured Content of ^{131}I in the Thyroid [$M_{res}(t_m,k)$ in kBq]

The measured content of ^{131}I in the thyroid of subject k at time t_m, $M_{res}(t_m, k)$, is estimated as follows:

$$M_{res}(t_m, k) = CF(dev)AC(dev, a)[X_{th}(k) - b(a)X_{bg}(k)]B(t_m, dev, k), \qquad \text{(A2.1)}$$

where dev is an index representing the type of measuring device; t_m is the time of measurement, in days, counted from the time of the accident; $CF(dev)$ is the device-specific calibration factor measured with a bottle thyroid phantom, in kBq μR^{-1} h or in kBq count s^{-1}. Distribution: log-normal with a GSD that depends on the calibration conditions and is estimated to lie in the range from 1.1 to 1.4. $AC(dev, a)$ is an age correction factor applied to the device-specific calibration factor, dimensionless. The values of $AC(dev, a)$, which are based on calculations using phantoms of different sizes, take into account the variation with age of the thickness of tissue separating the thyroid from the radiation device (*20*). Distribution of $AC(dev, a)$: lognormal with GSD = 1.1. $X_{th}(k)$ is the signal measured against the thyroid, μR h^{-1}, counts min^{-1} or counts. $X_{bg}(k)$ is the signal measured in the room in the absence of the subject, μR h^{-1}, count s^{-1} or count. $b(a)$ is the age dependent coefficient for shielding background by a human body; the values are 1 for ages 0–7, and 0.95 for ages 8–18. Distribution is triangular with values of minimum, mode and maximum of [0.95; 1; 1] for ages 0–7 and [0.90; 0.95; 1] for ages 8–18. $B(t_m, dev, k)$ is the fractional contribution of ^{131}I into signal from thyroid, unitless. Its value was taken to equal to 1, although it is now known that the contribution of ^{137,134,136}Cs in the body may have been relatively important. The determination of average values of $B(t_m, dev, k)$ according to region of residence, time of measurement, and age of subject remains to be assessed.

Because the thyroid measurements in Ukraine were made with collimated devices, it was considered that the surface contamination on other parts of the body did not influence the results of the measurements.

Normalized Time-Integrated Activity of ^{131}I in the Thyroid [$IRA(t_m, k)$ in days]

Using the ecological model described in Appendix 1, the time-integrated activity of ^{131}I in the thyroid, normalized to the activity in the thyroid at the time of the direct thyroid measurement, t_m, is calculated as

$$IRA(t_m, k) = \int_0^T \frac{y_4(t, k)}{y_4(t_m, k)}\, dt = \frac{EA(k)}{y_4(t_m, k)}, \qquad \text{(A2.2)}$$

where $T = 64$ day is the end of the period over which the activity of ^{131}I in the thyroid of the subject is integrated (from 26 April to 30 June 1986). This period was used in the questionnaire for queries on residence history and dietary habits. At the end of June 1986, the ^{131}I activity in the thyroids of the subjects had decreased to very low levels. Changing the value of T from 64 days to infinity would result in trivial increases in the thyroid dose estimates.

Deterministic Instrumental Thyroid Dose ($D^{det}_{k,instr}$ in mGy)

The instrumental dose is calculated in the same way as the ecological dose. The only difference between the two is that the thyroidal content of ^{131}I at time t_m is derived from the direct thyroid measurement instead of the ecological model. It follows from Eq. (A1.19) in Appendix 1 that the instrumental thyroid dose for subject k can be calculated as

$$D^{det}_{k,instr} = \frac{K_u \cdot E_{th}}{m_{th}(k)} \cdot M_{res}(t_m, k) \cdot IRA(t_m, k), \qquad \text{(A2.3)}$$

where $m_{th}(k)$ is the age-dependent mass of the thyroid (g). Values are taken from Table A1.1. Distribution of $m_{th}(k)$ is lognormal with GSD = 1.6. E_{th} is the mean energy absorbed in the thyroid per decay of ^{131}I in the thyroid (MeV/decay). Distribution: triangular with a mode of 0.22, a minimum of 0.2, and a maximum of 0.23. K_u is a unit conversion factor equal to 13.82 (Bq/kBq) (g/kg) (J/MeV) (s/day) (mGy/Gy). The deterministic values of the instrumental thyroid doses have been calculated using the parameter values that are designated as central estimates, geometric means, modes, values, or averages throughout this Appendix as well as in Appendix 1.

Stochastic Instrumental Thyroid Dose ($D^{stoch}_{k,instr}$ in mGy)

The stochastic values of the instrumental thyroid dose have been calculated using Eq. (A2.3). In the stochastic mode, distributions of individual instrumental doses for every cohort member were calculated with a Monte Carlo procedure. For that purpose, probability distributions were assigned to most of the parameter values, as indicated in Appendix 1 and in this Appendix. It was assumed in the Monte Carlo calculations that all parameters were independent. In each trial of stochastic mode, a value of the instrumental dose was estimated using randomly selected values of the parameters weighted according to their probability distributions. One thousand values of the instrumental dose were calculated in that manner for every cohort member. Finally, the arithmetic ($D_{k,instr}^{stoch,AM}$) and geometric ($D_{k,instr}^{stoch,GM}$) means of the 1,000 values of the instrumental dose as well as the geometric standard deviation of their distribution (GSD_k^{1000}) were estimated for every cohort member.

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