Chapter 2

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Different levels of thyroid dose individualization of the Ukrainian donors in Chernobyl tissue bank

In order to accumulate and centralize information on the radioinduced Chernobyl thyroid cancers, an international Chernobyl Tissue Bank (CTB) has been established. By 2012, it comprised 2,267 specimens of thyroid tumoral tissues from residents of Ukraine who had been operated on within the time period from 1990 to 2011 (see Chapter 6). These specimens were verified by experts in the course of 20 international panel meetings. The specimens accumulated in the CTB represent a material of paramount importance for various studies of the effects of ionizing radiation exposure at the molecular and genetic levels.

Over the last 25 years elapsed after the Chernobyl catastrophe, substantial experience was accumulated in the field of the individual thyroid and other organs doses reconstruction due to the accidental exposure. At that, in the ecological-dosimetry models, the reliability and adequacy of the resulting doses entirely depend on the available data (the levels and dynamics) of radioactive fallout on the soil, vegetation, milk, and other foodstuffs in different regions, as well as the information on the life style of residents during the time period of exposure (their movements over the radioactively contaminated area, diet composition, and amount of foodstuffs being consumed). The results of more than 150,000 direct measurements of ^{131}I activity in the thyroid of children and adolescents, which were performed in May-June of 1986 in the northern, most contaminated regions of Ukraine, are particularly important for the development of thyroid reconstruction models.

The results of direct measurements of thyroid activity that were performed in May-June 1986 are very helpful both to estimate the individual thyroid doses for the subject under the measurement and to development and parameterization of the reconstruction models. Hence, the *four-level system of thyroid dose reconstruction* was developed so that to estimate the internal thyroid doses for individuals or population groups of all regions of Ukraine. This system has been applied for the CTB donors' thyroid doses reconstruction. The decision on which levels of the four-level system is to be used for a CTB subject depends on the available information on the existence of direct measurement in 1986 and place of living (settlement, raion and oblast) in 1986. In all cases, the thyroid dose estimates either directly used the result of measurement performed for the subject, or indirectly used the results of thyroid measurements performed for other inhabitants in the settlements of raion in the form of relationships between the result of thyroid measurements in different age-gender groups and environmental characteristics.

Individual thyroid doses were estimated in 2009-2011 for 1,933 of 2,267 Ukrainian CTB subjects [1] in the framework of EU Contract 211712 *"CTB - The Chernobyl Tissue Bank-Coordinating International Research on Radiation Induced Thyroid Cancer"*. For each subject the central (deterministic) value of the thyroid dose was estimated and also the uncertainty of such estimates, which are due to different types of errors in the parameters of the ecological and biokinetic models that were used.

The objectives of this chapter are to present:

- the subdividing CTB cohort over the Groups and subgroups depending on the available individual data and characteristics;
- a brief description of the dosimetry models that were used for the reconstruction of individual thyroid doses of Ukrainian CTB subjects of different Groups and subgroups, as well as a description of the approaches used to assess the uncertainties attached to the dose estimates for the subjects of the different groups;
- the generalized results of the dose estimates provided for the Ukrainian CTB subjects.

Geographical distribution of the subjects

It was found that in May-June of 1986, the CTB subjects were distributed over 24 oblasts of Ukraine and Crimea autonomous republic (Fig. 2.1). At that about 60% of the exposed UkrCTB subjects resided in areas of highly-contaminated northern oblasts (Kyiv, Chernihiv, and Zhytomyr), whereas 16% of CTB-subjects resided in areas with moderate levels of radioiodine fallout, and 23% of Ukrainian CTB subjects resided in areas with low levels of radioiodine fallout. In addition, there were 9 subjects who did not reside in Ukraine at the time of the accident.

Types of exposure condition

Ukrainian CTB cohort may be subdivided according to the following exposure conditions:

- Subjects aged *one year or more* at the time of the accident exposed *as a result of radioactivity-contaminated foods consumption* in 1986.
- Subjects aged *less than one year* at the time of the accident exposed as a result of *breast feeding* in May-June 1986.
- Subjects born in May-June 1986 who have been exposed partly *in utero,* and partly as a result of *breast feeding.*
- Subjects born within the time period from July 1986 to March 1987 exposed *in utero.*
- *Non-exposed subjects* born after March 1987.

Distribution of the UkrCTB subjects by age at the time of the accident

For a unit of ^{131}I intake due to the consumption of contaminated foods the dose to the child's thyroid exceeds the dose to adults. This is mainly because the significantly smaller size of children's thyroid gland, in comparison to that for adults [2]. Thus, the *age* at which child's exposure occurred is one of the critical parameter in the dose reconstruction. Table 2.1 shows the distribution of the UkrCTB subjects by age at the time of accident.

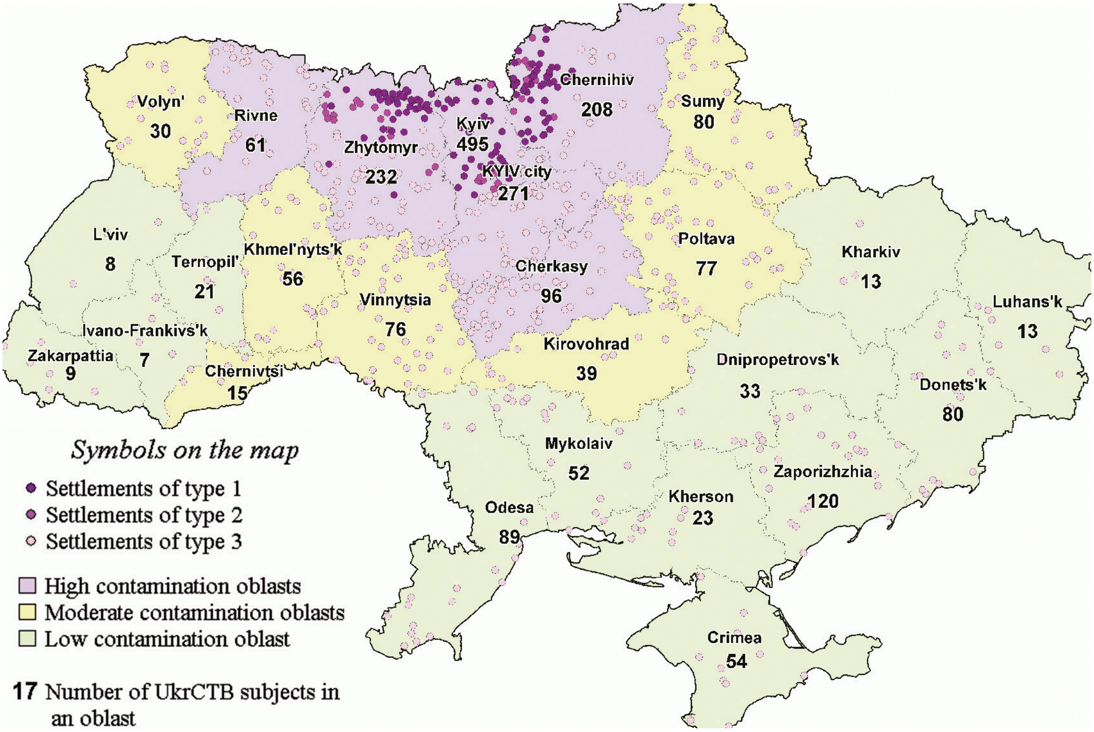

Figure 2.1. Geographical distribution of the Ukrainian CTB subjects over the settlements of different types in the oblasts with high, moderate and low ^{131}I Chernobyl ground deposition.

Table 2.1
Distribution of Ukrainian CTB subjects by age at the time of the accident

Age, years	Number of UkrCTB subjects	
	boys	girls
< 1	87	39
1 – 4	327	84
5 – 9	366	73
10 -14	433	127
15 – 17	256	59
18	32	10
Total exposed	1501	392
Born after March 1987	294	80
Total for the UkrCTB cohort	1795	472

In Ukrainian CTB cohort 64 subjects were exposed *in utero*. The thyroid dose to the fetus depends to a large degree on the level of ^{131}I intake by the mother due to consumption of food, as well as on the embryo and fetus gestational age (period of mother's pregnancy) during exposure. The greater was the gestational age during the exposure period (from 26 April to 30 June 1986), the higher was the fetal dose per unit of ^{131}I intake by the mother [3]. Table 2.2 presents the distribution of the Ukrainian CTB subjects who were exposed *in-utero* according to the period of mother's pregnancy at the time of accident.

Table 2.2
Distribution of *in utero* exposed UkrCTB subjects according to the period of mother's pregnancy at the time of the accident

Period of mother's pregnancy on 26 April 1986 (days)	**Number of subjects**
≤ 0	9
1-30	5
31-60	7
61-90	5
91-120	4
121-150	6
151-180	9
181-200	2
> 200 (subjects born before July 1986)	17
Total	*64*

Distribution of Ukrainian CTB subjects by method of thyroid dose reconstruction

In the *thyroid dose system* that is used for the CTB (*TDS-CTB*) all CTB subjects were subdivided into several groups depending on the availability of direct measurements in 1986 performed either directly on the subject, or on other persons in the region of his (her) residence at the time of accident.

Group 1. CTB subjects who had a *direct thyroid measurement* performed in May-June 1986 and were administered a *special interview* concerning the consumption rate of contaminated foods (essentially cow milk and leafy vegetables), as well as their possible changes of residence in May-June 1986 [4]. The interviews of these subjects were performed in framework of Ukraine-U.S. cohort study [4,5].

Group 2. CTB subjects who had individual direct thyroid measurements carried out in May-June 1986 [6], but without personal interviews.

Group 3. CTB subjects with neither individual direct thyroid measurements in May-June 1986 nor personal interviews. These subjects are further subdivided into three subgroups depending on their residence or non-residence in the raions of different oblasts where direct measurements were performed among the local population.

Subgroup 3.1 CTB subjects who resided in May-June 1986 in the settlements where direct thyroid measurements were performed on some inhabitants (*settlement of type 1*).

Subgroup 3.2 CTB subjects who resided in the settlements where no direct thyroid measurements were performed, but such measurements were performed on some inhabitants of neighboring settlements of the raion (*settlement of type 2*).

Subgroup 3.3 CTB subjects who were residents of the regions (raions, oblasts) where direct thyroid measurements were not carried out at all (*settlement of type 3*).

Group 4. CTB subjects who were exposed *in utero*. This group includes those born within the period from April 26, 1986 to March 31, 1987.

The distribution of the CTB subjects into the four groups is presented in Table 2.3.

Table 2.3
Distribution of CTB subjects by the groups and subgroups

Dosimetry group and subgroup	Description of dosimetry group	Number of UkrCTB subjects*
Group 1	CTB subjects who had direct thyroid measurements and personal interviews	**165**
Group 2	CTB subjects who had direct measurements of ^{131}I in the thyroid in May-June of 1986 but had no personal histories	**19**
Group 3	CTB subjects who had neither personal histories nor direct measurements of ^{131}I activity in thyroid in April-June of 1986:	**1685**
Subgroup 3.1	- residents of settlements of *type 1*	*613*
Subgroup 3.2	- residents of settlements of *type 2*	*43*
Subgroup 3.3	- residents of settlements of *type 3*	*1029*
Group 4	CTB subjects who were exposed *in utero*	**64**
Non-irradiated		**310**
Total		**2243**

*For 24 CTB-subjects the settlement of their residence in 1986 could not be identified

Table 2.4 shows the distribution of the Ukrainian CTB subjects of four above-mentioned groups according to date of birth: children, adults, and exposed *in utero*.

As shown in Tables 2.3 and 2.4, Group 3, consisting of 1,685 CTB subjects (mainly children) is the most numerous.

Table 2.4
Distribution of the CTB subjects of different groups according to date of birth

Dosimetry groups of CTB cohort	Date of birth				Total Number
	before 26.04.1968	26.04.1968-26.04.1986	May-June 1986	July 1986 - March 1987	
	Adults	Children	Exposed *in utero* + postnatal	Exposed *in utero*	
Group 1	-	165	-	-	165
Group 2	-	19	-	-	19
Group 3	43	1642	-	-	1685
Group 4	-	-	17	47	64
Total	43	1826	17	47	1933

Members of Groups 1 and 2 (~9.5% of all irradiated Ukrainian CTB subjects), for whom information on direct measurements of radioiodine activity in the thyroid in May-June 1986 is available, have the highest degree of dose individualization.

Because the members of Group 3 had no direct thyroid measurements in 1986, a mean settlement-age-gender specific dose is assigned to subjects of these groups. The adequacy of estimate of mean group-specific dose depends whether the direct thyroid measurements were provided in the settlement of residence of the subject or in a neighboring settlement. Thus, the highest degree of adequacy of an individualized dose estimations have the members of subgroup 3.1 residing in 52 settlements of type 1, and then, in the descending order, the members of subgroups 3.2 and 3.3 who were residents of 27 and 486 settlements of types 2 and 3, respectively. The distribution of settlements of different types in which CTB subjects were residing in 1986, for different oblasts of Ukraine, is shown on Figure 2.1. Settlements of type 1 and 2 are located predominantly in the most contaminated northern oblasts, while settlements of type 3 are located in the less contaminated southern oblasts.

General structure of models in TDS-CTB

Figure 2.2 shows the structure of the four-level *TDS-CTB* used to calculate the thyroid doses for the subjects of each of four groups as well as the common and group-specific initial data sets used in the calculation models of each level.

As shown in Figure 2.2, the data on the daily fallouts of ^{131}I on the ground in the settlements of residence are used as input in the *TDS-CTB* models of each of four groups. Daily fallouts over the 10 days of accidental release for each settlement are estimated using a model of atmospheric transfer [7, 8], allowing to calculate the daily dynamics of ^{131}I concentrations in vegetation and milk during May-June 1986.

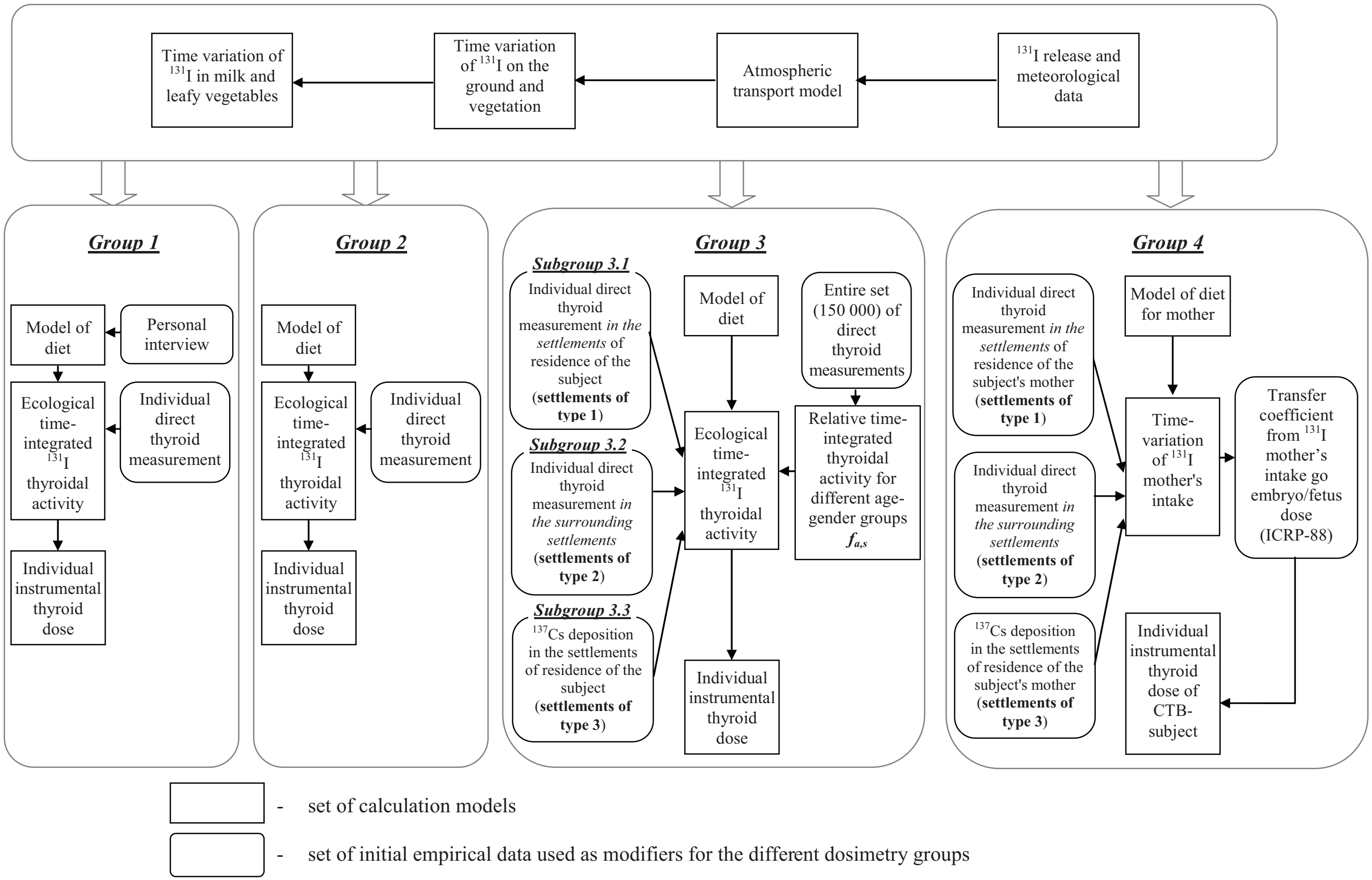

Figure 2.2. General scheme of models and initial data sets used in the different dosimetry groups in TDS-CTB.

Table 2.5
Reference daily consumption rates of milk and leafy vegetables used in the *TDS-CTB* for Groups 2, 3, and 4; AM and STD are the arithmetic mean and standard deviation, respectively

Age	Rural areas				Urban areas			
	Boys		Girls		Boys		Girls	
	AM	STD	AM	STD	AM	STD	AM	STD
Milk consumption rate (*L d*$^{-1}$)								
1	0.67	0.42	0.62	0.46	0.48	0.33	0.40	0.32
2	0.66	0.44	0.57	0.38	0.33	0.27	0.33	0.28
3	0.64	0.46	0.52	0.38	0.34	0.28	0.29	0.28
4	0.63	0.39	0.58	0.37	0.36	0.38	0.30	0.25
5	0.69	0.47	0.52	0.41	0.39	0.41	0.30	0.22
6	0.69	0.47	0.57	0.40	0.31	0.28	0.29	0.21
7	0.65	0.45	0.50	0.36	0.32	0.23	0.30	0.25
8	0.70	0.55	0.49	0.36	0.35	0.35	0.29	0.35
9	0.73	0.61	0.52	0.41	0.30	0.33	0.21	0.16
10	0.79	0.60	0.45	0.39	0.37	0.39	0.21	0.18
11	0.77	0.58	0.40	0.33	0.46	0.57	0.25	0.28
12	0.72	0.57	0.48	0.50	0.47	0.41	0.23	0.21
13	0.78	0.65	0.47	0.51	0.47	0.62	0.27	0.23
14	0.78	0.65	0.47	0.41	0.44	0.35	0.20	0.19
15	0.72	0.62	0.43	0.36	0.44	0.50	0.20	0.29
16	0.83	0.74	0.48	0.40	0.44	0.50	0.20	0.29
17	0.83	0.66	0.44	0.37	0.44	0.50	0.20	0.29
18	0.83	0.66	0.44	0.37	0.44	0.50	0.20	0.29
Consumption rate of leafy vegetables (*kg d*$^{-1}$)								
1	0.011	0.014	0.010	0.011	0.014	0.017	0.007	0.006
2	0.015	0.021	0.013	0.019	0.013	0.017	0.015	0.017
3	0.019	0.020	0.017	0.020	0.012	0.013	0.014	0.018
4	0.021	0.018	0.022	0.024	0.020	0.024	0.017	0.020
5	0.025	0.022	0.017	0.017	0.019	0.017	0.017	0.016
6	0.029	0.025	0.023	0.021	0.025	0.024	0.024	0.028
7	0.027	0.025	0.027	0.022	0.020	0.026	0.025	0.021
8	0.029	0.028	0.029	0.026	0.020	0.020	0.018	0.017
9	0.028	0.020	0.026	0.027	0.024	0.030	0.023	0.019
10	0.037	0.032	0.033	0.025	0.031	0.031	0.020	0.018
11	0.036	0.031	0.032	0.025	0.032	0.036	0.037	0.038
12	0.035	0.027	0.036	0.031	0.028	0.026	0.034	0.028
13	0.039	0.029	0.030	0.023	0.026	0.018	0.038	0.037
14	0.036	0.032	0.031	0.030	0.035	0.031	0.042	0.036
15	0.044	0.031	0.036	0.027	0.027	0.022	0.033	0.032
16	0.038	0.028	0.044	0.041	0.027	0.022	0.033	0.032
17	0.046	0.032	0.035	0.028	0.027	0.022	0.033	0.032
18	0.046	0.032	0.035	0.028	0.027	0.022	0.033	0.032

The "ecological" time-integrated thyroid activity of ^{131}I is calculated for the subjects of Groups 1, 2 and 3 using the time-variation of ^{131}I in leafy vegetables and milk and also the model of diet.

For the subjects of Group 1 the model of diet was developed using the information from the personal interviews [4] on the daily consumption of different components of diet: cow milk, goat milk, private milk, shop milk, sour milk, kefir, and leafy vegetables. The information on the settlements of residence in May and June 1986, duration of his (her) stay in each residence, dates of arrival/departure from each settlement of residence was also clarified during the personal interviews of the CTB subjects of Group 1.

Due to the absence of personal dietary data for the subjects of Groups 2, 3, and 4, the reference age- and gender-dependent consumption rates of milk and leafy vegetables were used for the calculation of the ^{131}I daily intake (Table 2.5). It was also assumed that the subjects of Groups 2, 3, and 4 were not relocated from their settlements of residence in April-June 1986.

Group-specific modifiers are established for the ecological time-integrated ^{131}I thyroidal activity are also shown in Figure 2.2 for each group.

The following initial data sets were used for establishing the modifiers:

- *subjects of Group 1 and 2*: the results of direct thyroid measurements of ^{131}I activity for the CTB subject in May-June 1986;
- *subjects of subgroup 3.1:* the results of direct thyroid measurements of ^{131}I activity performed in May-June 1986 among the inhabitants (not the CTB subjects) in the settlement of staying of the CTB subject (settlement of type 1);
- *subjects of subgroup 3.2:* the results of direct thyroid measurements of ^{131}I activity performed in May-June of 1986 among the inhabitants in the settlements of the raion surrounding the settlement of residence of the CTB subject in 1986 (settlement of type 2);
- *subject of subgroup 3.3*: data on ^{137}Cs ground deposition in the settlement of residence of the CTB subjects (settlement of type 3).

The modifiers of subgroups of Group 3 are developed by analyzing the results of ~150,000 direct thyroid activity measurements taken in May-June 1986 in the Northern oblasts of Ukraine.

The model of thyroid dose reconstruction applied for the subjects of Group 4 (exposed *in utero*) includes the calculation of time-variation of ^{131}I intake for mother. At that the modifiers are dependent on the type of settlement of a CTB-subject's mother's residence in 1986.

Using the ecological time-integrated ^{131}I thyroidal activity corrected by the correspondent modifiers and age-gender dependent thyroid mass [9], the individual "instrumental" thyroid doses (in deterministic and stochastic modes) are calculated for each CTB subject of Groups 1, 2 and 3. The individual "instrumental" thyroid doses for the subjects of Group 4 are calculated using the transfer coefficients from ^{131}I mother's intake to embryo-fetus dose, which are significantly changing with the period of mother's pregnancy [3].

Parameters of models in TDS-CTB

The central estimates and uncertainty distributions that were selected for the main parameters of the ecological and dosimetry models in *TDS-CTB* are presented in Table 2.6, with the exception of age-dependent lung ventilation rate and biological half-time of iodine excretion from the thyroid, which are provided in Table 2.7.

Table 2.6
Central estimates and statistical characteristics of the distributions of the main parameters used in *TDS-CTB*. GM is the geometric mean; GSD is the geometric standard deviation [8,10-18]

Name of parameter	Notation	Unit	Central estimate (AM)	Distribution type	Distribution parameters
Radioactive decay constant for ^{131}I	λ^r	d^{-1}	$8.62 \cdot 10^{-2}$	Constant	—
Energy absorbed in thyroid per ^{131}I radioactive decay	$E^{I-131,th}$	*MeV*	0.20	Constant	—
^{131}I activity decrease factor in leafy vegetables due to culinary treatment	$K^{r,cul,gr}$	*Unitless*	0.8	Uniform	min=0.6, max=1.0
Effective transfer coefficient that describes excretion of iodine into human milk	TC_{ef}^{I}	$day \cdot L^{-1}$	0.4	Censored lognormal	GM =0.37, GSD = 1.4 min=0.25, max=0.89
Effective half time of iodine excretion into human milk	$T_{ef}^{I,m}$	*day*	0.58	Censored lognormal	GM =0.5, GSD =1.7 min=0.21, max=1.33
Transfer factor of ^{131}I from lungs to blood	$B^{r,inh}$	*Unitless*	0.61	Triangular	mode=0.58, min=0.40, max=0.85
Transfer factor of ^{131}I from blood to thyroid	$B^{I,th}$	*Unitless*	0.3	Triangular	mode=0.25, min=0.15, max=0.5
Deposition velocity of ^{131}I on the ground (dry conditions)	$V^{I,soil}$	$m \cdot d^{-1}$	600	Censored lognormal	GM=540, GSD=1.6, min=210, max=1380
^{131}I mass interception factor by vegetation (wet mass)	$K_{M}^{r,gr}$	$m^2 \cdot kg^{-1}$	0.25	Triangular	mode=0.2, min=0.1, max=0.45
Grass yield (wet mass)	M^{biom}	$kg \cdot m^{-2}$	0.75	Triangular	mode=0.75, min=0.5, max=1.0

Continuation of Table 2.6

Short half-time of elimination of ^{131}I from the grass surface by weathering	$T_1^{I,gr}$	*d*	7.0	Censored lognormal	GM=6.9, GSD=1.2, min=4.6, max=9.5
Long half-time of elimination of ^{131}I from the grass surface by weathering	$T_2^{I,gr}$	*d*	28.0	Censored lognormal	GM=27.5, GSD=1.2, min=12, max=37
Daily consumption of fresh grass by cow	I^{gr}	*kg d⁻¹*	45	Triangular	mode=45, min=30, max=60
Biological half purification period of milk from ^{131}I	$T^{I,cow}$	*d*	1.1	Censored lognormal	GM=1.0, GSD=1.4, min=0.5, max=1.96
Transfer factors for ^{131}I from daily cow's intake to concentration in cow's milk	TF^I	$d{\cdot}L^{-1}$	0.01	Censored lognormal	GM=0.0065, GSD=2.5, min=0.00, max=0.04

Table 2.7
Central estimates and ranges of age-dependent parameters in *TDS-CTB*: lung ventilation rate and biological half-time of iodine excretion from the thyroid [2,12,19]

Age (years) a	**Lung ventilation rate (*m³·d⁻¹*)**			**Biological half-time of iodine excretion from the thyroid (*d*)**		
	AM	min	max	AM	min	max
0	2.9	1.4	5.4	15	7.1	28
1	5.6	2.7	10.6	20	9.4	38
2	6.5	3.1	12.3	22	10.4	42
3	7.4	3.5	14.0	25	11.8	47
4	8.3	3.9	15.6	28	13.2	53
5	9.3	4.4	17.5	30	14.2	57
6	10.4	4.9	19.6	38	18.0	72
7	11.5	5.4	21.7	46	21.7	87
8	12.6	5.9	23.7	54	25.5	102
9	13.6	6.4	25.8	62	29.3	117
10	14.8	7.0	28.0	70	33.1	132
11	16	7.5	30.2	72	34.0	136

Continuation of Table 2.7

Age (years) a	Lung ventilation rate ($m^3 \cdot d^{-1}$)			Biological half-time of iodine excretion from the thyroid (*d*)		
	AM	min	max	AM	min	max
12	17.2	8.1	32.4	74	35.0	140
13	18.3	8.7	34.7	76	35.9	144
14	19.5	9.2	36.9	78	36.9	147
15	20.3	9.6	38.4	80	37.8	151
16	20.7	9.8	39.2	82	38.7	155
17	21.2	10.0	40.0	84	39.7	159
18	21.6	10.2	40.8	87	41.1	164

Main equations of TDS-CTB for the subjects of different groups

Groups 1 and 2

The following equation was developed to calculate the individual dose $D_{1,2}^{ind}$ for subject *i* of dosimetry group 1 or 2:

$$D_{1,2}^{ind} = z \frac{E^{I-131}}{M_{a,s}} A_i^{ecol} \cdot K_i^{sc} , \qquad (2.1)$$

where:

$M_{a,s}$ is the thyroid mass of the subject of age *a* and sex *s*, *g*;

E^{I-131} is the energy absorbed by the thyroid per ^{131}I radioactive decay, *MeV per decay*;

A_i^{ecol} is the individual "ecological" time-integrated thyroid activity calculated using the models of environmental iodine transport and the biokinetic model, *kBq·d*;

K_i^{sc} is the *individual "scaling factor"* which adjusts the ecological integrated activity A_i^{ecol} according to the results of the direct thyroid measurement for the CTB-subject *i*, *unitless*;

z is a unit conversion coefficient, equal to:

$$13.82 \frac{Bq}{kBq} \cdot \frac{g}{kg} \cdot \frac{J}{MeV} \cdot \frac{s}{day} \cdot \frac{mGy}{Gy} .$$

In equation 2.1, the individual scaling factor K_i^{sc} for the subject *i* is estimated as:

$$K_i^{sc} = \frac{Q_i^{I,mes}}{Q_i^{I,ecol}(t^{mes})} \quad (2.2)$$

where:

$Q_i^{I,\ mes}$ is the measured [131]I activity in the thyroid of subject *i*, *kBq*;

$Q_i^{I,ecol}(t^{mes})$ is the estimate of thyroid activity at the time of measurement t^{mes} using the ecological environmental iodine transport model and the biokinetic model, *kBq*.

<u>*Groups 3*</u>

For the subjects in dosimetry Group 3, the individual thyroid dose D_i^{ind} is calculated as the *settlement-specific age-gender group averaged* thyroid dose $D_{a,s,j}$, where *a* and *s* are the age and the gender of the age-gender group the subject *i* belongs to, and *j* is the settlement of residence of the subject in April-June 1986.

Subgroup 3.1 (Settlements of type 1, j):*

$$D_{3.1}^{ind} = D_{a,s,j*} = z\frac{E^{I-131}}{M_{a,s}} A_{a_{ref},s,j*}^{mes} \cdot f_{a,s}$$
$$A_{a_{ref},s,j*}^{mes} = \frac{1}{N}\sum_{k=1}^{N}\frac{A_{k,a,s,j*}^{ecol} \cdot K_k^{sc}}{f_{a,s}} \quad (2.3)$$

where

N is the number of residents *k* (not the subjects of Ukrainian CTB) with direct thyroid measurements in the settlement of residence *j** of the UkrCTB subject under consideration;

$f_{a,s}$ is the relative time-integrated thyroidal activity for the subjects of *a-s* group [20] (Table 2.8);

$A_{a_{ref},s,j*}^{mes}$ is the settlement-specific time-integrated thyroidal [131]I activity for gender *s* in the *reference age group* a_{ref} for the settlement *j**, *kBq·d*;

$A_{k,a,s,j*}^{ecol}$ is the ecological time-integrated [131]I thyroidal activity calculated for the resident *k* (not an UkrCTB subject) of age-gender group *a-s* the CTB-subjects belonged to in the settlement *j**, *kBq·d;*

K_k^{sc} is the individual scaling factor of subject *k* (not the subjects of Ukrainian CTB) with direct [131]I thyroid measurement in te settlement *j** of CTB-subject *i* staying.

Table 2.8
Parameters of the relative time-integrated thyroidal ^{131}I activity function $f_{a,s}$ for different age-gender groups. GM is the geometric mean; GSD is the geometric standard deviation

Age	Relative time-integrated thyroidal activity ($f_{a,s}$)							
	Urban areas				Rural areas			
	Girls		Boys		Girls		Boys	
	GM	GSD	GM	GSD	GM	GSD	GM	GSD
0	0.81	3.3	0.61	3.0	0.58	3.1	0.47	3.2
1	0.81	3.3	0.61	3.0	0.58	3.1	0.47	3.2
2	0.81	2.8	0.62	3.0	0.64	2.8	0.55	2.8
3	0.77	2.5	0.61	2.8	0.64	2.7	0.54	2.6
4	0.86	2.4	0.67	2.5	0.70	2.6	0.56	2.9
5	0.97	2.5	0.86	2.5	0.70	2.6	0.59	2.6
6	1.0	2.3	0.86	2.3	0.77	2.5	0.66	2.6
7	1.0	2.1	0.85	2.3	0.75	2.2	0.70	2.4
8	0.88	2.4	0.79	2.4	0.76	2.4	0.72	2.5
9	0.91	2.2	0.81	2.2	0.80	2.4	0.79	2.4
10	0.92	2.2	0.81	2.2	0.81	2.4	0.84	2.2
11	0.97	2.1	0.91	2.1	0.89	2.2	0.85	2.3
12	0.95	2.1	0.94	2.1	0.95	2.1	0.90	2.2
13	1.0	2.1	0.96	2.2	1.0	2.1	1.0	2.2
14	1.1	2.1	1.1	2.2	1.0	2.1	1.1	2.2
15	1.1	2.2	1.1	2.3	1.0	2.3	1.2	2.4
16	1.2	2.4	1.1	2.5	1.0	2.4	1.3	2.5
17	1.2	2.5	1.1	2.3	1.0	2.4	1.1	2.4
18	1.1	2.8	1.0	3.0	0.95	2.7	1.1	2.1

Subgroup 3.2 (Settlements of type 2, j^{**}):

$$D_{3.2}^{ind} = D_{a,s,j^{**}} = z\frac{E^{I-131}}{M_{a,s}} \cdot \frac{A_{a_{ref},s,j^{**}}^{ecol}}{K_{s,raion}^{scal}} \cdot f_{a,s}$$

$$K_{s,raion}^{sc} = \frac{1}{J}\sum_{j^*=1}^{J} \frac{A_{a_{ref},s,j^*}^{ecol}}{A_{a_{ref},s,j^*}^{mes}} \qquad (2.4)$$

where

j is the number of settlements j^* with direct thyroid measurements in the *raion* where the settlement j^{**} of CTB-subject is located.

A_{a_{ref},s,j^*}^{ecol} is the settlement-specific time-integrated thyroid ^{131}I activity for gender s in the reference age-interval a_{ref} in the settlement j^* estimated using the ecological model, *kBq·d*;

$K^{sc}_{s,raion}$ is the *raion-specific scaling factor* for the settlements of type 2 (j^{**}).

Subgroup 3.3 (Settlements of type 3, j^{***}):

$$D^{ind}_{3..3} = D_{a,s,j***} = z \frac{E^{I-131}}{M_{a,s}} \frac{A^{ecol}_{a_{ref},s,j***}}{K^{\sigma}_{s,j***}} f_{a,s} \quad (2.5)$$
$$K^{\sigma}_{s,j***} = B(\sigma_{Cs,j***})^{\beta}$$

where

$K^{\sigma}_{s,j***}$ is the scaling factor for the settlements of type 3 (j^{***}) (Table 2.9);

$\sigma_{Cs,j***}$ is the ^{137}Cs ground deposition in settlement j^{***}, *kBq·m*$^{-2}$*;*

Table 2.9
Parameters used to estimate the scaling factors $K^{\sigma}_{s,j***}$ (Subgroup 3.3). AM is the arithmetic mean, STD is the standard deviation, GM is the geometric mean, GSD is the geometric standard deviation. $K^{\sigma}_{s,j***} = B(\sigma_{Cs,j***})^{\beta}$

Location	Gender	***B***		***β***	
		GM	GSD	AM	STD
Rural	Boys	0.59	1.1	0.36	1.03
	Girls	0.47	1.1	0.36	1.03
Urban	Boys	0.36	1.5	0.61	1.10
	Girls	0.34	1.5	0.58	1.10

Groups 4 (exposed in-utero)

As shown in Figure 2.2, the reconstruction of the thyroid dose for the CTB-subjects exposed *in-utero* [3] includes a model the CTB-subject's mother diet and CTB-subject's mother ^{131}I intake with food in May-June 1986. The data sets used as the modifiers in the model of thyroid dose reconstruction for the CTB-subjects of Group 4 ($K^{sc}_{i,mother}$) are identical to those developed in the reconstruction models for dosimetry subgroups 3.1, 3.2, and 3.3, and dependent on the type of settlement in which the mother resided in May-June 1986. Thus, the individual dose to CTB subjects *i* due to *in-utero* exposure ($D^{ind}_{i,F}$) is described by the following equation:

$$D_F^{ind} = K_{i,mother}^{sc} \times \int_0^T h_F(\tau(t)) \times q_{i,mother}^{ecol}(t)dt \quad (2.6)$$

where

$$K_{i,mother}^{sc} = \begin{cases} K_i^{sc} & \text{if the mother had a direct thyroid measurement in May - June 1986} \\ K_{j*}^{sc} & \text{if the mother resided in a settlement of type 1 (j*)} \\ K_{s,raion}^{sc} & \text{if the mother resided in a settlement of type 2 (j**)} \\ K_{s,j***}^{\sigma} & \text{if the mother resided in a settlement of type 3 (j***)} \end{cases} \quad (2.7)$$

$q_{i,mother}^{ecol}(t)$ is the daily intake of ^{131}I by the mother, estimated using the ecological ^{131}I-transport model, $Bq \cdot d^{-1}$.

$\tau(t)$ is the stage of pregnancy of the mother of the CTB subject at time *t* counted from 26 April 1986, *days*;

$h_F(\tau)$ is the fetal thyroid dose per unit intake of ^{131}I by the mother [21] dependent on the stage of pregnancy τ $Gy \cdot Bq^{-1}$;

Estimation of thyroid dose uncertainties for the UkrCTB subjects

The uncertainties of the thyroid doses estimations in the CTB subjects of different dosimetry groups were calculated using a Monte-Carlo procedure. For this purpose, probability distributions were assigned to most of parameter values. The types and characteristics of the distributions of some of the parameters are shown in Table 2.6. It was assumed in the Monte-Carlo procedure that all parameters were independent. One thousand values of the individual dose were calculated for every CTB subject. Finally, the arithmetic and geometric means of the 1,000 values of instrumental doses as well as the geometric standard deviation minimum, maximum and 25%, 50%, 75% percentiles of these distributions were estimated for every CTB subject.

The Monte-Carlo procedure used for estimating the dose uncertainties differed in some respect for the different groups and subgroups, since different parameters and functions were applied.

Estimates of individual thyroid doses for the UkrCTB subjects

Individual thyroid doses were estimated for 1,933 Ukrainian CTB subjects. Doses have not been reconstructed for 24 CTB subjects (because the settlements of their staying in 1986 could not be identified), and for 310 non-irradiated subjects born after March 1987.

For each of the subjects the thyroid dose and their uncertainties were estimated from the environmental transport and biokinetic models adapted to the information available for the different groups and subgroups (Figure 2.2) using a Monte-Carlo simulation procedure with 1,000 trials for every CTB subject.

Table 2.10 shows the arithmetic mean as well as the 50%, 25%, 75% percentiles and the minimum and maximum values of individual doses estimated for the subjects of different age-groups in different dosimetry groups. For 15 of the 64 subjects of Group 4, the individual thyroid doses are estimated to be negligibly small, and taken to be equal to zero.

Table 2.10
General groups of individual thyroid doses estimated for the UkrCTB subjects of the different groups and subgroups

Age intervals, years	Number of subjects	Individual thyroid doses, Gy					
		Mean	Percentiles			Min	Max
			50%	25%	75%		
Group 1							
0-4	44	1.9	0.43	0.81	2.3	0.046	13
5-9	42	1.2	0.16	0.54	1.8	0.025	7.2
10-14	69	0.75	0.055	0.31	1.1	0.001	5.3
15+	10	1.6	0.045	0.25	2.5	0.023	8.5
All ages	165	1.2	0.13	0.48	1.4	0.001	13
Group 2							
0-4	13	2.7	0.43	0.72	3.8	0.008	13
5-9	3	0.033	0.028	0.032	0.037	0.027	0.039
10-14	2	0.33	0.021	0.33	0.63	0.021	0.63
15+	1	0.3	0.3	0.3	0.3	0.3	0.3
All ages	19	1.9	0.099	0.53	3.2	0.008	13
Subgroup 3.1							
0-4	164	0.26	0.1	0.15	0.23	0.04	5.2
5-9	159	0.096	0.039	0.051	0.068	0.021	2.7
10-14	186	0.049	0.024	0.03	0.034	0.013	1.1
15+	104	0.037	0.024	0.026	0.028	0.014	0.37
All ages	613	0.12	0.027	0.043	0.11	0.013	5.2
Subgroup 3.2							
0-4	16	2	0.09	0.15	0.91	0.04	24
5-9	5	1.4	0.017	0.2	3	0.016	4.1
10-14	13	0.1	0.021	0.075	0.14	0.014	0.44
15+	9	0.031	0.013	0.027	0.035	0.011	0.091
All ages	43	0.93	0.028	0.091	0.19	0.011	24
Subgroup 3.3							
0-4	293	0.3	0.036	0.11	0.21	0.001	1.9
5-9	223	0.061	0.014	0.034	0.068	0.002	0.8
10-14	283	0.033	0.008	0.017	0.037	0.001	0.45
15+	229	0.029	0.008	0.017	0.031	0.001	0.59
All ages	1029	0.09	0.012	0.031	0.08	0.001	1.9
Group 4							
All ages	49	0.1	0.001	0.014	0.08	<0.001	2.1

The results presented in Table 2.10 indicate that the highest doses were estimated for the CTB subjects of dosimetry groups 1 and 2, and also for the subjects of subgroup 3.2. The high doses in the subjects of these groups and subgroups are the consequence of their residence in May-June 1986 in the most radioactively-contaminated areas (Figure 2.1). The lowest doses are estimated for the subjects of subgroup 3.3 because these subjects were staying in the areas with moderate and low radioactive contamination in 1986. As shown in Table 2.10, the younger children (aged 0 to 4 years) received higher thyroid doses than any other age group in all dosimetry groups and subgroups.

The general characteristics of the uncertainties of the estimated individual thyroid doses are presented in Table 2.11 in terms of mean, min, max and geometric standard deviation (GSD) of individual geometric standard deviation for the different groups and subgroups. The data of Table 2.11 clearly show that the uncertainties in the reconstructed individual thyroid dose estimates increase from Group 1 to Group 4. In dosimetry Group 3, the highest uncertainties in the estimated individual doses were found for the subjects of subgroup 3.3. This is due to the fact that direct thyroid measurements of ^{131}I activity are not used to justify the ecological dose estimation for this subgroup. The substantial uncertainties in the thyroid dose estimates for the CTB subjects exposed *in utero* (Group 4) are related to: (1) the complexity of modeling the iodine metabolism in the embryo/fetus and the transfer of ^{131}I from the mother to fetus at different stages of pregnancy, and (2) a number of difficulties in modeling the mother's diet in May-June 1986.

Table 2.11
Average values of geometric standard deviation (GSD) of individual geometric standard deviation for the subjects of diferent groups and subgroups. N is the number of subjects

Dosimetry group and subgroup	**N**	**GSD of individual thyroid doses**		
		Mean	Min	Max
1	165	1.5	1.3	4.7
2	19	1.5	1.4	1.7
3-1	613	2.9	2.3	4.6
3-2	43	3.3	2.3	5.2
3-3	1029	3.6	3.1	4.5
4	49	3.8	2.8	8.7

Table 2.12 presents the distribution of the Ukrainian CTB subjects of different dosimetry group/subgroup over the intervals of individual thyroid dose irrespectively of the age. As shown in Table 2.12, the CTB members of Group 1 are distributed rather evenly by dose value within the interval up to 5 Gy. Individual doses for 17 of 19 members of Group 2 are also within the dose interval up to 5 Gy. In subgroup 3.1 for 99% of subjects the estimated individual thyroid doses do not exceed 1 Gy, and for about 55% of members of this group the thyroid doses do not exceed 0.05 Gy. In the subgroup 3.2 the relative distribution of the subjects by the dose interval is similar to that in subgroup 3.1. For 97% of members of subgroup 3.3 the individual thyroid doses were estimated to be less than 0.5 Gy, and for 79% as being less than 0.1 Gy. For 47 of 64 Ukrainian CTB members

of Group 4, i.e., those who were partly or entirely exposed *in utero*, individual thyroid doses were estimated to be less than 0.05 Gy. For one subject of Group 4 the individual thyroid dose estimation is greater than 0.5 Gy.

Table 2.12
Distributions of UkrCTB subjects according to the interval of estimated mean individual thyroid dose

Thyroid dose interval, Gy	**Group and Subgroup**					
	1	2	3.1	3.2	3.3	4
	Number of UkrCTB subjects					
<0.05	23	5	335	18	681	47
0.05-0.1	12	-	109	5	129	9
0.1-0.2	15	-	96	10	124	2
0.2-0.5	36	4	52	1	62	5
0.5-1	24	4	13	4	22	-
1-2	22	-	5	1	11	-
2-5	27	4	2	3	-	1
5-10	4	1	1	-	-	-
>10	2	1	-	1	-	-
Entire cohort	165	19	613	43	1029	64

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