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THYROID EXPOSURE IN BELORUSSIAN AND UKRAINIAN CHILDREN AFTER THE CHERNOBYL ACCIDENT AND RESULTING RISK OF THYROID CANCER

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“Thyroid Exposure in Belorussian and Ukrainian Children after the Chernobyl Accident and Resulting Risk of Thyroid Cancer”

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1. INTRODUCTION

Main objectives of the BfS Project StSch4240 *Thyroid Exposure of Belarusian and Ukrainian Children due to the Chernobyl Accident and Resulting Thyroid Cancer Risk* were:

- to establish improved estimates of average thyroid dose for both genders and for each birth-year cohort of the period 1968 - 1985 in Ukrainian and Belarusian settlements, in which more than 10 measurements of the ^{131}I activity in the human thyroid have been performed in May/June1986
- to explore, whether this dosimetric database can be extended to neighboring settlements
- to establish improved estimates of average thyroid dose for both genders and for each birth-year cohort of the period 1968 - 1985 in Ukrainian and Belarusian oblasts (regions) and larger cities
- to document the thyroid cancer incidence for the period 1986 – 2001 in Ukraine and Belarus and describe morphological characteristics of the cancer cases
- to assess the contribution of the baseline incidence to the total thyroid cancer incidence in the two countries and identify regional and temporal dependencies
- to perform analyses of excess risks in settlements with more than 10 measurements of the ^{131}I activity in the human thyroid.

The project has been conducted in the period 6 December 1999 to 31 March 2004. It is a collaborative study of the *GSF - Forschungszentrum für Umwelt und Gesundheit* with four partner institutes: *Institute of Radiation Medicine and Endocrinology* (Minsk), *Ukrainian Radiation Protection Institute* (Kyiv), *Institute of Endocrinology and Metabolism of the Academy of Medical Sciences of Ukraine* (Kyiv), and *Association of Victims of Radiation Disasters and Accidents* (Moscow). During the course of the project, the Institute of Radiation Medicine and Endocrinology was dissolved. The scientists involved, however, continued to work for the project. Also, the *Association of Victims* was restructured to become the *All-Russian Public Organization of Invalids "Chernobylets", Scientific Center "FENIX"* (Moscow).

The project has been accompanied by the BFS project StSch 4299 *Range of applicability of epidemiological studies with aggregate data for risk factor determination*. The purpose of that project is to explore by simulation calculations to which degree there is an ecologic bias in the risk studies performed in the frame of the present project. The results of project StSch 4299 indicate that the ecologic bias of excess absolute risk estimates is small because:

- radiation is the dominating cause of thyroid cancer among those who were children or adolescents in the highly contaminated areas at the time of the accident
- there is no indication that the dose-response for thyroid cancer after exposures during childhood is non-linear in the dose range of 0.05-1.0 Gy (Jacob et al. 1999, Ron et al. 1995)
- the variability of average doses in the age-gender groups of the considered settlements is larger than the variability of individual doses within the groups
- the number of ^{131}I activity measurements exceeds considerably the number of the age-gender groups in the different settlements (by a factor of 5)
- there is no indication of a relevant correlation between dose and screening within the highly contaminated areas.

The material for the present report is quite extensive. In order to facilitate the reading, the report has been structured in a main part that contains the main results, and 11 Appendices that contain more specific information. Several of the Appendices have Annexes.

2. DOSIMETRY

2.1 UKRAINE

The main objective of this Section is to carry out a detailed estimation of the thyroid doses of the Ukrainian population due to the incorporation of ^{131}I that was released during the Chernobyl accident. The developed system has three levels of dosimetric support for different types of epidemiological research. The first level is the estimation of individual thyroid doses. This level is used outside of the present project in a classical cohort study (Ukrainian-American Thyroid Project, Tronko et al. 2003). The second and the third level comprise the estimation of average doses to age-gender groups in settlements with more than 10 measurements of the ^{131}I activity in the human thyroid, and in oblasts and larger cities of Ukraine. The settlement-specific doses are used in the analysis of excess risks in highly contaminated areas (Section 4.2), the oblast-specific doses in estimates of the baseline incidence and its regional and temporal variations (Section 4.1).

This Section is a summary of a more extensive report in Appendix 1.

MATERIALS AND METHODS

General equations

The variation with time of the ^{131}I activity in the thyroid $A_{a,s}(t)$, (*Bq*), for a subject of age *a* and gender *s* is defined by two main processes:

- Uptake of ^{131}I by the thyroid, which is described by a function $U_{a,s}(t)$, ($Bq \cdot d^{-1}$);
- Excretion of ^{131}I from the thyroid, which is taken to be exponential. It is characterized by the effective constant of elimination of ^{131}I from the thyroid, λ_a^{ef}, (d^{-1}), that in turn is the sum of the biological elimination constant, λ_a^{biol}, (d^{-1}), and of the radioactive decay constant of ^{131}I, λ_I, (d^{-1}).

The function $A_{a,s}(t)$ can be described by the following equation:

$$A_{a,s}(t) = \int_0^t U_{a,s}(\tau) e^{-\lambda_a^{ef}(t-\tau)} d\tau \,. \qquad (2.1)$$

The thyroid dose, $D_{a,s}^{th}$, (*Gy*) is

$$D_{a,s} = \frac{\alpha}{M_a} \int_0^\infty A_{a,s}(t) dt = \frac{\alpha}{M_a} Q_{a,s} \,, \qquad (2.2)$$

where

α , ($J/Bq·d$), is the energy absorbed in the thyroid due to the radioactive decay of a unit activity of ^{131}I during one day;

M_a , (kg), is the age-dependent thyroid mass, averaged for boys and girls;

$Q_{a,s}$, ($Bq·d$), is the time-integrated activity of the ^{131}I content in the thyroid for a subject of age-gender group "*a-s*".

Ecological model

The variation with time of the ^{131}I activity in the thyroid, $A_{a,s}(t)$ in eq. (2.1), can be estimated based on an ecological model that describes the transport of ^{131}I through the environment and in people. The model takes into account the processes of deposition on the ground and vegetation, the uptake by ruminants, the transfer of ^{131}I into milk, the consumption of contaminated foods by humans, as well as the inhalation intake with contaminated air, and the uptake and retention of ^{131}I in the thyroid. The output of the model is the variation of the ^{131}I activity in the thyroid during the period of exposure. Most of the ^{131}I release from the Chernobyl reactor occurred during the first few days after 26 April 1986 and the radioactive decay limited the period of concern about intakes of ^{131}I with the diet to about two months.

Fundamental to the model are the measurements and estimates of the radionuclide depositions in the locations of interest after the accident. The total deposition of ^{137}Cs has been measured in all settlements throughout Ukraine. Daily depositions of both, ^{137}Cs and ^{131}I, have been estimated using a mesoscale atmospheric transport model. The model has been validated by application to data on Chernobyl radionuclide release rates and comparison with measured ^{137}Cs depositions in Ukraine.

Three pathways of ^{131}I intake were considered in the ecological model: inhalation, ingestion of leafy vegetables and ingestion of milk. The most important sources of ^{131}I intake were for most of the persons (1) consumption of milk and (2) consumption of leafy vegetables during May-June 1986. A mathematical description of the ecological model is given in Appendix 1.

Measurements of the ^{131}I activity in the human thyroid

The ^{131}I activity in the thyroid has been measured for about 130 000 inhabitants of the Ukrainian territories affected by the Chernobyl accident. Most of the measurements were performed between 20 and 40 days after the accident. The thyroid dose of the measured inhabitants k was derived from the measured activity $\tilde{A}_{k,a,s}$, (Bq), in their thyroid. The methodology of thyroid measurements used in Ukraine in April-June of 1986 (groups of population, territorial distribution of the measurements, and descriptions of the measuring devices and their calibration) have been presented in detail in previous publications (Likhtarev et al. 1994 and 1999). The measurements have been re-evaluated in the frame of the present project (see Appendix 1). The evaluation of the measurement results takes into account the presence of radiocesium in the human body. The corresponding correction factors depend on the ages of the measured person and on the time after the accident.

Definitions and principles of thyroid dose estimations

The thyroid dose $D_{a,s}$ estimated based on the generic function $A_{a,s}(t)$ that has been calculated with the ecological model for a subject of age *a* and gender *s* who remained in a settlement with a specified level of ^{131}I deposition is called the *"ecological thyroid dose"*.

The *"individual scaling factor"* for a measured person *k* is defined by:

$$K_k^{scal} = \frac{\widetilde{A}_{k,a,s}}{A_{a,s}(t_{meas})}, \qquad (2.3)$$

where $A_{a,s}(t_{meas})$ is the model estimation of the thyroid activity at the time of measurement, t_{meas}. An "*instrumentally individualized thyroid dose"* is then obtained by

$$D_{k,a,s} = K_k^{scale} D_{a,s} . \qquad (2.4)$$

If $D_{a,s}$ is based on data on the individual's diet and behavior (from responses to a questionnaire), then the resulting $D_{k,a,s}$ is called "*questionnaire-based instrumentally individualized thyroid dose"*.

Individual doses $D_{k,a,s}$ (and related time-integrated activities) are used for the estimation of:

- settlement-specific thyroid doses for different age-gender groups, and
- age-gender thyroid doses aggregated for all the settlements in an oblast.

First level of thyroid dose estimation: instrumentally individualized doses

The first level of thyroid dose estimation comprises individuals with measurements of the ^{131}I activity in the thyroid. If available, results of interviews on diet and behavior are taken into account, otherwise a reference diet and behavior is used.

For the majority of the approximately 130 000 Ukrainians, for whom the ^{131}I activity in the thyroid was measured in May/June 1986 (including ~99 000 children and adolescents), instrumentally individualized thyroid doses could be estimated. Results of large-scale interviews of rural and urban inhabitants (9500 questionnaires in Chernihiv Oblast in 1992, 3000 questionnaires in Kyiv Oblast in 1993, and 2300 questionnaires in Zhytomyr Oblast in 1994) on the diet and food consumption rates in May/June 1986 were used for the development of reference age-gender dependent consumption rates.

Soon after the beginning of the accident, the inhabitants of the settlements, which were close to the Chernobyl nuclear power plant, were evacuated to the territory of Kyiv, Chernihiv, and Zhytomyr Oblasts. Their thyroid doses were caused by exposures before, during and after evacuation. These settlements were because of this complicated exposure structure not included in the present study.

Second level of thyroid dose estimation: age- and gender-specific doses in settlements with measurements of the ^{131}I activity in the human thyroid

The second level of thyroid dosimetry considers settlement-specific doses for different age and gender groups in locations where measurements of the ^{131}I activity in the human thyroid were performed in May/June 1986.

Time integrated activities $\tilde{Q}_{ref,s,j}$ of 12-14 year olds with gender *s* in settlement *j* and generic normalized activities $f_{a,s}$ for the age group *a* were derived from the time integrated activities of all measured persons (see Appendix 1). Thyroid doses in the 36 age-sex groups in each of the settlements with a sufficient number of ^{131}I measurements were obtained according to

$$\overline{D}_{a,s,j} = \tilde{Q}_{ref,s,j} \cdot f_{a,s} \cdot \alpha \; / M_a . \tag{2.5}$$

Third level of thyroid dose estimation: age- and gender-specific doses in all oblasts of Ukraine

For the determination of the age- and gender-specific doses in the oblasts of Ukraine, the settlements were divided into three groups:

- Group 1 includes settlements *j* in which measurements of the ^{131}I activity in the human thyroid were performed in May/June 1986.
- Group 2 includes settlements j^* in which no measurements of the ^{131}I activity in the human thyroid were performed in May/June 1986, but which are located in raions (districts) where measurements were made in other settlements.
- Group 3 includes the remaining settlements j^{**}.

Age- and gender-specific doses in the oblasts were obtained by averaging the doses in the settlements of the oblast. The settlement were weighed according to their population.

<u>*Thyroid dose estimation for the settlements of group 2*</u>. The individual scaling factors K_k^{scal} for measured inhabitants *k* living in settlements of group 2 were averaged over the single raions in order to obtain scaling factors K_{raion}^{scal} for each of the raions, in which measurements of the ^{131}I activity in the human thyroid were performed in May/June 1986. The values of K_{raion}^{scal} were in the range of 0.9 (for girls in Chernihiv town) to 8.4 (for boys in Luhyny Raion in Zhytomyr Oblast) and decreased with decreasing ^{137}Cs activity.

The integrated activity $Q_{a,s,j*}$ of age group *a* and gender group *s* in settlement *j** was obtained according to:

$$Q_{a,s,j*} = \frac{Q_{ref,s,j*}^{ecol}}{K_{raion}^{scal}} f_{a,s}, \tag{2.6}$$

where $Q_{ref,s,j*}^{ecol}$ is the time-integrated thyroidal ^{131}I activity for a representative of reference age and gender *s* in the settlement j^* according to the ecological model.

Thyroid dose estimation for the settlements of Group 3. The scaling factors for settlements of group 2 were approximated by an analytical function $K^{scal}(\sigma_{Cs})$ of the radiocesium activity per unit area σ_{Cs}. The integrated activity $Q_{a,s,j**}$ of age group a and gender group s in a settlement $j**$ was obtained according to:

$$Q_{a,s,j**} = \frac{Q^{ecol}_{ref,s,j**}}{K^{scal}(\sigma_{Cs,j**})} \cdot f_{a,s} \,, \tag{2.7}$$

where $\sigma_{Cs,j**}$ is the radiocesium activity per unit area in settlement $j**$.

RESULTS

First level of thyroid dose estimation: instrumentally individualized doses

About 130 000 instrumentally individualized thyroid doses were reconstructed for Ukrainian children, adolescents and adults. All measurements were made in Kyiv, Zhytomyr, and Chernihiv oblasts, which were the most contaminated oblasts after the Chernobyl accident. Some characteristics of the distribution of the measurements concerning their appropriateness for the estimation of settlement-specific doses are given in Table 2.1.

Second level of thyroid dose estimation: age- and gender-specific doses in settlements with measurements of the ^{131}I activity in the human thyroid

For the present analysis, only measurements in settlements with more than ten SRP measurements or more than four measurements with better devices were taken into account. Also, measurements, for which the gender of the measured persons is not known, were excluded. The remaining number of instrumentally individualized doses was 75 000 (Table 2.1).

The 95% range of average age- and gender specific thyroid doses in the 684 Ukrainian settlements with measurements and with reconstructed population structure in 1986 is 0.015 – 0.36 Gy. There are a few small settlements with considerably higher thyroid doses, up to 17 Gy for 1-year old boys.

Third level of thyroid dose estimation: age- and gender-specific doses in all oblasts of Ukraine

Oblast-specific thyroid dose estimates for 36 age- and gender groups are given in Appendix 1 for the 24 oblasts of Ukraine, Kyiv City, the Crimean Republic, and the City of Sevastopol'.

The estimated thyroid doses for different Ukrainian oblasts are between 3 mGy (Zakarpattya Oblast) and 84 mGy (Zhytomyr Oblast). The thyroid doses for particular age and gender groups in Zhytomyr Oblast are in the range 29-176 mGy. For Kyiv Oblast the range is 28-172 mGy); for Chernihiv Oblast 20-121 mGy. Two other oblasts with upper range doses in excess of 100 mGy are Rivne Oblast (23-149 mGy), and Cherkasy Oblast (18-117 mGy). In all cases, the highest doses are estimated for children who are 1 or 2 years old.

Table 2.1 Number of settlements and measurements of the ^{131}I activity in the human thyroid in Ukraine.

Type of population	Number of settlements	Number of thyroid measurements F	M	Unknown	Total
1. Total amount of measurements performed at the settlements					
1. All measurements	787	59 628	52 001	18 625	130 254
1.1 Evacuees	53	4911	4277	362	9550
1.2 Non-evacuees	734	54 717	47 724	18 263	120 704
2. Settlements where ≥ 10 thyroid measurements were made by SRP and/or ≥ 4 measurements were made by other devices [a)]					
2.1. Evacuees	51	4079	4069	-	8148
2.2 Non-evacuees: All	697	37 788	37 559	-	75 347
2.2.1 Rural	661	20 453	20 153	-	40 606
2.2.2 Urban	36	17 335	17 406	-	34 741
3. Settlements with thyroid measurements in the reference age-interval of 12-14 years old [a)]					
3.1.Evacuees	49	4069	4049	-	8118
3.2.Non-evacuees: All	619	36 899	36 807	-	73 706
3.2.1 Rural	584	19 566	19 401	-	38 967
3.2.2 Urban	35	17 333	17 406	-	34 739

[a)] Only measurements, for which the gender of the measured person is known, have been taken into account

Based on the oblast-specific thyroid doses, the entire territory of Ukraine can be subdivided into three zones:

- Zone of high thyroid doses (average dose of children and adolescents exceeding 35 mGy): Zhytomyr, Kyiv, Rivne, Chernihiv, Cherkasy oblasts;
- Zone of moderate thyroid doses (14-35 mGy): Volyn', Vinnytsia, Khmel'nyts'k, Chernivsi, Kirovohrad, Poltava, Sumy oblasts, Kyiv City and Autonomous Republic Crimea;
- Zone of low thyroid doses (13 mGy and less): the other 12 oblasts of Ukraine.

The location of the single oblasts and cities is shown in Fig. 4.1.

CONCLUSION

The approaches used for the three levels of thyroid dose estimations summarize the current status of retrospective thyroid dosimetry achieved in Ukraine up to the year 2003.

It is appropriate to identify a number of areas of dosimetric research needed for reducing the uncertainty associated with thyroid dose estimations:

- Modification of some parameters of iodine metabolism depending on the level of stable iodine in the diet. This is most important for areas with a deficiency of stable iodine including the north of Ukraine
- Clarification of the age-dependent thyroid mass for children and adolescents of Ukraine at the time of Chernobyl accident, as influenced by the level of dietary intake of stable iodine
- More precise description of reference diets, especially for young children at the time of the accident. This is because restrictions of milk and leafy vegetable consumption most likely were applied by parents to this subgroup of children
- Evaluation of the uncertainties of the ^{131}I deposition estimates and the ecological model parameters and their site-specificity
- Evaluation of the doses received by children aged less than 1 year at the time of accident.

2.2 BELARUS

There are larger uncertainties in the dosimetry for Belarus than for Ukraine, because the measurements were performed with detectors, which were not shielded against radiation coming from other parts (than the thyroid) of the human body or from contaminated clothes, and because there were often less good measurements conditions (outdoor measurements, care was not taken to remove contaminations of clothes or of part of the human body). Therefore, for each of the risk studies two different methods of dosimetry were applied.

For the assessment of the baseline contribution to the thyroid cancer incidence in the two countries, the evaluation of ^{131}I measurements and the semi-empirical model by FENIX (Section 2.2.1), and a radioecological model (Section 2.2.3) were used. The analyses of excess risks in the settlements with more than 10 measurements of the ^{131}I activity of the human thyroid were based on evaluations of these measurements by FENIX (Section 2.2.1) and by GSF (Section 2.2.2).

2.2.1 EVALUATION OF ^{131}I MEASUREMENTS AND THE SEMI-EMPIRICAL MODEL (FENIX)

The main objectives of this Section are:

- Critical examination and consistency checks of individual thyroid dose estimates in Belarus. Revision of individual thyroid doses where necessary
- Estimation of average age-dependent thyroid doses and associated uncertainties for Belarusian settlements with more than 10 measurements of ^{131}I activities in the human thyroid after the Chernobyl accident
- Application of the generalized model (semi-empirical model) developed by FENIX to provide age-dependent thyroid dose estimates and associated uncertainties in Belarusian settlements, for which not more than 10 measurements of ^{131}I activities in the human thyroid after the Chernobyl accident are available
- Estimation of average age-dependent thyroid doses for children and adolescents in 1986 in each of the Belarusian oblasts.

This Section is a summary of a more extensive report in Appendix 2.

MATERIALS AND METHODS

As described in detail in Appendix 2, input data used in the project were:

- a database with individual measurements of the ^{131}I thyroidal content carried out within a few weeks following the Chernobyl accident and subsequent estimates of individual thyroid doses based on those thyroid measurements using corresponding functions of the ^{131}I intake for about 126 000 Belarusian inhabitants (Tables 2.2 and 2.3)
- a database of the ^{137}Cs activity per unit area for all Belarusian settlements prepared by BelHydromet

- a database of the results of spectrometric measurements of various radionuclides, including ^{131}I, in environmental samples and foodstuffs carried out in May through July 1986, prepared by the Institute of Biophysics (Moscow)
- demographic data on Belarus.

Table 2.2. Characteristics of the data bank of individual thyroid dose estimates for the Belarusian people.

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

The main methods developed outside the framework of the project but used and further developed in the frame of the project were

- a method to assess individual thyroid doses for the Belarusian people on the basis of the results of measurements of individual content of ^{131}I in the thyroid
- the semi-empirical model to assess age-dependent average thyroid doses in Belarusian settlements where not a sufficient number of ^{131}I measurements were conducted.

Table 2.3. Characteristics of reliability of the thyroid measurements used to assess individual thyroid doses in the available database for Belarusian people depending on the conditions of measurements.

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

RESULTS

Thyroid doses in Gomel City

A critical examination of individual thyroid dose estimates in the data bank revealed an inconsistency in the data related to the residents of Gomel City: A systematic increase of the estimated doses with the time of measurements was observed. This was attributed to a possible overestimation of the contribution of inhalation to the total thyroid doses. The data were re-evaluated by assuming that the inhalation dose can be neglected. The re-evaluated dose estimates did not depend – as it should be - on the time of the measurement. They were by a factor of two lower than the old dose estimates. The re-evaluated dose estimates were used in the further calculations.

Thyroid doses in Minsk City

A re-evaluation of dose estimates for Minsk City was performed. Analysis of individual doses based on measured ^{131}I activity in thyroid showed that the main contributor to thyroid exposure to environmental ^{131}I for the residents of Minsk City was ingestion of contaminated, fresh milk rather than inhalation of contaminated air (Appendix 2). A main change in re-evaluating the doses was the use of age-dependent parameters like the effective clearance of ^{131}I from the thyroid and the thyroid mass (ICRP 1990). This implied compared to an earlier assessment an increase by 50% of the thyroid dose of young children who stayed in Minsk City in the period 26 April – 31 May 1986. There was less change for the other population groups.

The average thyroid dose of the population living in the city during April-May 1986 was estimated to be: 0.12 Gy for children aged 0 to 6 y; 0.037 Gy for children aged 7 to 17 y and 0.017 Gy for adults (Table 2.4). The average thyroid dose of the Minsk population that left the city in April-May, mainly for the more contaminated areas, was estimated to be about one order of magnitude higher than that for those who lived in the city.

Table 2.4 Thyroid doses of children of different age and of adolescents, who spent either the whole period 26 April – 31 May 1986 in Minsk, or at least a few days outside Minsk.

Group	Number of children	Characteristics of the distribution of thyroid doses (Gy)				
		10^{th} percentile	Median	Average	90^{th} percentile	Maxi-mum
0-6y, in Minsk	3742	0.0018	0.057	0.12	0.29	1.6
partly outside Minsk	549	0.040	0.50	0.86	2.1	12
7-17y; in Minsk	2593	0.0016	0.023	0.037	0.078	0.53
partly outside Minsk	327	0.021	0.20	0.41	0.90	6.6

Thyroid doses exceeding 10 Gy

In the data bank, thyroid dose estimates of 331 persons exceeded 10 Gy (Table 2.5), 77% of them are children of age 0-3. Taking into account that high doses have a significant influence on average thyroid dose estimates in the settlement, it was decided to investigate whether the “measured” doses exceeding 10 Gy were realistic.

Two observations led to the conclusion that the dose estimates exceeding 10 Gy are not particularly unreliable:

- Whereas only 4% of all measurements were in the class of highest reliability (Table 2.3), a much higher share (27%) of the high dose measurement belonged to that class
- The numbers of persons with thyroid doses exceeding 10 Gy observed in areas, where high doses were occurred, agreed well with the numbers predicted on the basis of the main characteristics (geometric mean and geometric standard deviation) of the individual dose distributions.

Table 2.5. Distribution of dose estimates exceeding 10 Gy over the four groups of reliability of ^{131}I activity measurements.

Dose range (Gy)	Number of people	Group of reliability			
		1	2	3	4
10 – 30	310	84	2	133	91
30 – 50	16	5	-	5	6
> 50	5	1	-	2	2
> 10	331	90	2	140	99

Age-dependent thyroid doses in Belarusian settlements with more than 10 measurements of the ^{131}I activity in the human thyroid

In the assessment of age-dependent thyroid doses the following information for each of the measured individuals was used:

- individual dose
- date of measurement
- exposure rate, assigned to the content of ^{131}I in the thyroid at the time of measurement
- date when the main fallout occurred in the vicinity of the settlement considered
- date of leaving (if the person left the settlement of residence in the first weeks after the accident)
- date when the cow of which milk was consumed, was first put on pasture.

Further, average values for the times in the latter two points were used for the different age groups of the settlement. In addition, some generic data as age-dependent milk consumption rates were used.

In the calculation (Appendix 2), it was assumed that:

- the inhalation dose in the single settlements was the same for the residents of same age
- the ingestion dose was proportional to the individual consumption of contaminated milk.

A list of output values is given in Annex 8 of Appendix 2. Gender-specific doses were estimated with the procedure described in Section 4.1. The 95% range of age- and gender specific thyroid doses in the 485 Belarusian settlements is 0.03 – 0.99 Gy. There are a few small settlements with considerably higher thyroid doses (Fig. 2.2), up to 17 Gy for 1-year old children.

Average age-dependent thyroid doses in Belarusian oblasts

In the semi-empirical model (Gavrilin et al. 1999), an improved differentiation between dry, wet and mixed depositions of radioiodine was introduced (Annex 3 of Appendix 2). This improved model was applied to estimate age-dependent thyroid doses for children and adolescents in Belarusian settlements, in which not more than 10 measurements of ^{131}I activity in the human thyroid were conducted in 1986. Age-dependent thyroid doses in Belarusian oblasts were then calculated by weighing the doses in the settlements (including those with more than 10 measurements) according to the population. The highest doses were obtained in Gomel Oblast (without Gomel City), ranging from1.0 Gy for 1-year old children to 0.15 Gy for 18-year old adolescents, followed by Gomel City (0.35 – 0.08 Gy). Minsk City and Brest and Mogilev oblasts had dose in the range 0.15 – 0.02 Gy.

2.2.2 EVALUATION OF ^{131}I MEASUREMENTS WITH A FACTORISATION METHOD (GSF)

The objective of the present Section is to derive from the individual data age-dependent doses for the birth years 1968-1986 for the cities of Gomel and Minsk, and for the settlements of rural areas in Belarus, where more than 10 measurements of the ^{131}I activity in the human thyroid have been performed in May/June 1986.

The determination is based on a factorisation approach, in which a generic age dependence and age-averaged values for each settlement are determined from the individual data. Separate determinations were made for the rural population and for urban residents of Gomel and Minsk cities. In the averaging procedure, estimated uncertainties of individual measurements according to their reliability class (Table 2.3) were taken into account.

In order to estimate the uncertainty of age-dependent dose values in the single settlements, also correlations between errors of measurements performed under similar conditions in each of the settlements were assessed. For the larger cities an assessment was made to take into account that people who did not stay the whole period of exposure in the cities are possibly overrepresented in the measurements. Most of them stayed in highly contaminated areas and were subject to considerably higher exposures.

This Section is a summary of a more extensive report in Appendix 3.

MATERIALS AND METHODS

Data base

Dose estimates were taken into account, which are based on measurements of the ^{131}I activity in the human thyroid that were performed in the period 2 May to 5 June 1986. In total, there were 5516 measured residents of Gomel City, 19 944 of Minsk City, and 94 942 of rural settlements in Gomel and Mogilev oblasts. About 30% of the measurements were performed for children or adolescents.

The data base contains information on the conditions under which the measurements were made (Annex 2 of Appendix 2). The individual determinations of integrated ^{131}I activities in rural settlements were performed under different conditions of reliability (Table 2.3). The data base contains for 31900 individuals from rural settlements (about 50% of them are children), measurements of the upper three reliability classes, and for 63042 individuals (about 20% of them children) measurements of the lowest reliability class. Measurements of residents of Gomel and Minsk cities were made under conditions of the three upper reliability classes.

The individual values are aggregated in each settlement into classes of higher and of lower reliability. According to the results of Appendix 2, uncertainties of the higher reliability measurements of the ^{131}I activity in human thyroid were assumed to be characterised by a geometric standard deviation (GSD) of 1.95, and of the lower reliability measurements of 2.5. For the propagation of errors to average doses in a settlement, it is taken into account how much of the uncertainty is correlated between the measured persons in the settlement.

General equations

The average thyroid dose $D_{a,j}$ for age group *a* of a settlement *j* is expressed as

$$D_{a,j} = Q_{a,j}\alpha / M_a , \tag{2.8}$$

where

α , *(J/Bq·d),* is the energy absorbed in the thyroid due to the radioactive decay of a unit activity of ^{131}I during one day;

M_a , (kg), is the age-dependent thyroid mass;

$Q_{a,j}$, *(Bq·d),* is the time-integrated activity of the ^{131}I content in the thyroid for age group *a* of a settlement *j*.

All measurements in rural (or urban) settlements are subdivided in sub-lists *i* with similar measurement conditions (same settlement, same measurement team, same device, same day of measurement). The average integrated ^{131}I activity in age group *a* in a sub-list *i* is expressed as:

$$Q_{a,i} = G_i \cdot f_a , \tag{2.9}$$

where f_a is normalized to the number of age groups 1 – 18 corresponding to the birth years 1968 to 1985

$$\sum_{a=1}^{18} f_a = 18 . \tag{2.10}$$

For a given age dependence f_a, the average integrated ^{131}I activity G_i is expressed by

$$G_i = \frac{1}{ni} \cdot \sum_{a=0}^{19} \sum_{k=1}^{nai} Q_{k,a,i} / f_a , \tag{2.11}$$

where $Q_{k,a,i}$ is integrated ^{131}I activity of the measured person *k* and *nai* is the number of measured persons in age-group *a* in sub-list *i*, and

$$ni = \sum_{a=0}^{19} nai \tag{2.12}$$

is the total number of measured persons in sub-list i. The age group a=0 corresponds to children born in 1986, the age group 19 to adults.

An iterative procedure (Appendix 3, Heidenreich et al. 2001) is applied to derive G_i and f_a:
Step 1. G_i is calculated with eq. (2.11) and the starting values $f_a = 1$, $a = 0, \ldots, 19$.
Step 2. f_a is calculated according to

$$f_a = \frac{1}{na} \sum_{i}^{Ni} \sum_{k=1}^{nai} Q_{k,a,i} / G_i \,, \qquad (2.13)$$

with G_i from the previous step. The summation extends over all Ni settlements or groups with similar measurement conditions in settlements and na is the total number of measured persons belonging to age group a.

Step 3. G_i is calculated according to eq.(2.11) with f_a from the previous step.
Steps 2 and 3 are repeated until the procedure has converged.

Rural settlements

For each rural settlement j, separate determinations of average integrated ^{131}I activities G_{hj} and G_{lj} are made for the individuals aggregated in the groups of higher and of lower reliability measurements, respectively. For this purpose, eq. (2.11) is used summing over all measured persons in a settlement with measurements belonging to the corresponding group of reliability.

In the further calculation, measurement uncertainties are differentiated between components that are correlated and uncorrelated between individuals of the group. A correlated error is, *e.g.*, a systematic wrong handling of the device during the measurements or during the calibration by a measurement team. Uncorrelated errors, *e.g.*, result from counting statistics during the measurement. For the higher reliability class, the correlated part of the uncertainty was assumed to correspond to a GSD of 1.2, and the uncorrelated part of 1.9. For the lower reliability class, the correlated part of the uncertainty was assumed to correspond to a GSD of 1.3, and the uncorrelated part of 2.4.

For each settlement a weighted average G_{Wj} is calculated from G_{hj} and G_{lj} by taking correlated and uncorrelated errors into account. Furthermore, the uncertainty of the weighted average is calculated.

Gomel and Minsk cities

In the determination of thyroid doses of the urban population of Gomel and Minsk cities it is accounted for that a fraction of the population had stayed in highly contaminated areas in the weeks after the accident. Separate calculations of average integrated ^{131}I activities G were made for the group of individuals who had stayed in these areas and the group of those who had not. An average integrated activity G_R is then calculated according to weights determined by the fraction of population which had stayed in these areas

RESULTS

Age dependence of integrated activities

The age dependencies f_a in rural settlements and in the cities have the same general behaviour (Fig. 2.1). The integrated activity of 18-year old adolescents is twice as large as the integrated activity of 1-year old children. However, there are also differences: Urban children in the age range 5 to 7 years (birth years 1981 to 1979) have up to 20% larger, and in the age range of 10 to 14 years (birth years 1976 to 1972) smaller relative values than rural children.

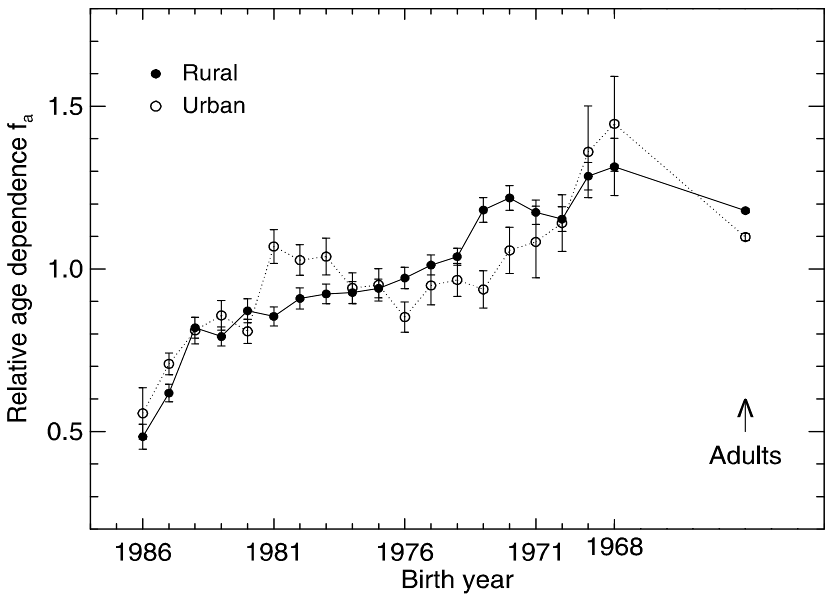

Fig.2.1. Relative age dependence f_a of the integrated ^{131}I activity for the urban population (Gomel and Minsk cities) and for the remaining settlements (rural). The error bars indicate one standard deviation.

In order to investigate whether the aggregation of measured individuals of rural settlements is sufficiently homogeneous with respect to age dependence, separate determinations were performed and compared for residents of raion centres and other rural settlements, for Gomel and Mogilev oblasts, for the evacuated and the relocated population, and for individuals with measurements of higher and lower reliability (Appendix 3). Given the estimated uncertainties, the results show that the use of separate determinations for these groups is not necessary and it is justified to use the same age dependence for all residents of these rural settlements.

Distribution of normalized integrated activities of measured persons

The distribution of the ratios $Q_{kai} / G_i f_a$ for the measured persons k gives information on the variability of individual dose estimates in the age group a. The distribution reflects both, the individual variability of true doses and uncertainties uncorrelated between the individuals. Therefore, the width of distribution is an upper bound for the distribution of the true individual values in each of the groups.

The distributions of $Q_{ka} / G f_a$ for rural and urban individuals have coefficients of variation of about 1.25. The distribution for urban inhabitants is wider than for rural inhabitants. The distributions are intermediate to normal and lognormal. Significantly less (more) very low doses are observed than expected on a basis of a normal (lognormal) distribution.

In a similar analysis of integrated activities measured in Ukraine (Heidenreich et al. 2001), the GSD of the distribution has been estimated by assuming a lognormal distribution. A value of 2.27 was obtained. Estimating the GSD under the same assumption, a values of 2.65 is obtained in the present analysis for Belarus (Table 2.6), reflecting the higher quality (smaller uncertainty) of the measurements in Ukraine.

Table 2.6 Properties of the distributions of the ratios $Q_{kai} / G_i f_a$ for measured rural and urban inhabitants. The arithmetic mean of the distributions is by definition 1.0. The GSD is calculated from the coefficient of variation under the assumption that the distribution is lognormal.

Group of individuals	Percentiles of distribution			Coefficient of variation	GSD
	2.5	50	97.5		
Rural	0.052	0.70	3.9	1.24	2.62
Urban	0.035	0.69	4.7	1.28	2.67

Average integrated activities in rural settlements

Results on dose distribution for all settlements with more than 10 measurements of the ^{131}I activity in the human thyroid are given in Appendix 3. Exemplary results for four rural settlements are presented in Table 2.7. For each of the 487 settlements with more than 10 measured individuals, age dependent settlement average doses were calculated for the birth years 1968 - 85 by multiplying the weighted averages G_{Wj} of integrated ^{131}I activities with the age dependence f_a determined for rural settlements (Fig. 2.1).

The coefficient of variation CV_{Wj} of the (weighted) individual integrated activities is, in general, larger for towns than for small villages, in which the contamination level of the consumed milk is more homogeneous. The coefficient of variation CW_{Gwj}, however, is in general smaller for towns because of the larger number of measurements. The average over all settlements of CV_{Gwj} has a value of about 0.5. Assuming a lognormal distribution, this corresponds to a GSD of 1.6, which is consistent with the GSD of about 1.5 estimated independently by geostatistical methods (Section 2.3).

Table 2.7. Distributions of average integrated ^{131}I activities for measured individuals of rural settlements. Given are the number of measured individuals n_{meas} in each settlement, and the percentiles of the distribution of individual values. Also given are the weighted settlement average G_{Wj}, the coefficient of variation CV_{Wj} of the weighted values, and the coefficient of variation CV_{Gwj} of G_{Wj}.

Settlement	n_{meas}	Percentiles (kBq day)			G_{Wj} (kBq day)	CV_{Wj}	CV_{Gwj}
		2.5	50	97.5			
Bragin	2441	62	1042	7375	2046	1.59	0.27
Dubrovnoe	264	104	2042	15750	3687	1.07	0.37
Borets	12	25	508	2960	783	1.03	0.63
Slavgorod	1166	5	104	667	166	2.79	0.49

Average integrated activities in towns

Average integrated ^{131}I activity of persons who stayed inside the city were according to the factorisation method for Gomel City by a factor of 6, and for Minsk City by a factor 13 smaller than for those who stayed some time of the first weeks after the accident in highly contaminated areas. This is consistent with what has been found in the analysis of FENIX (Section 2.2.1).

The fraction of population that stayed in contaminated areas is not known. A sensitivity analysis was performed starting with the number of measurements among people who stayed some time in contaminated areas. It was assumed that a percentage P_{meas} of these people was measured. This implied that the people who stayed some time in the highly contaminated areas constitute a percentage P_{HC} of the total city population (Table 2.8) Within a rather wide range of reasonable assumptions, the average integrated activity G_R in the two cities is affected by less than 15%. Values corresponding to P_{meas} = 50% were used in the calculation of age dependent average doses for Gomel and Minsk cities.

Thyroid dose

Based on the average integrated activities G_W for rural settlements and G_R for the two cities, age-dependent integrated activities were calculated according to eq. (2.9). Estimates of thyroid doses were then obtained according to eq. (2.8). Results were similar to those obtained with the method described in Section 2.2.1.

Table 2.8. Assumed percentages P_{meas} of people with measurements among those who stayed some time in highly contaminated areas. The table gives the resulting percentages P_{HC} of the city population that stayed in highly contaminated areas and the resulting estimated average integrated ^{131}I activity G_R.

P_{meas} (%)	Gomel City		Minsk City	
	P_{HC} (%)	G_R (kBq day)	P_{HC} (%)	G_R (kBq day)
70	0.39	302	0.20	116
50	0.54	305	0.29	117
30	0.90	310	0.50	120
10	2.72	339	1.45	133

2.2.3 RADIOECOLOGICAL MODEL

OBJECTIVE

Measurements of the ^{131}I activity in the human thyroid after the Chernobyl accident are not available for the larger part of Belarus. It is the objective of this Section to describe the development of a radioecological model that allows estimating thyroid doses for the whole population of Belarus. The model and results of applications are described in detail in Appendices 4 and 8.

MATERIALS AND METHODS

Outline of the model

The thyroid exposure for the Belarusian population after the Chernobyl accident was due to ingestion and inhalation of short-lived iodine isotopes. The most important pathway was the ingestion of ^{131}I with milk. Thyroid exposure due to inhalation was important only for small groups of people who were evacuated shortly after the accident in not contaminated areas and for those people who did not consume locally produced food.

The radioecological model estimates the thyroid exposure due to the consumption via the pathway pasture-cow-milk (Fig. 2.2). The starting point is the ^{137}Cs activity per unit area, which is used to estimate the ^{131}I deposit by means of a site-specific ^{131}I/^{137}Cs-ratio. The initial contamination of grass is estimated taking into account the yield of pasture grass, the deposition mode (dry/wet) and the amount of rainfall. The activity in milk is estimated from the time-dependent activity in grass by means of the transfer factor feed-milk and the biological half-life of iodine in milk. The thyroid dose is the result of the ^{131}I intake with milk considering age-dependent consumption rates and dose coefficients.

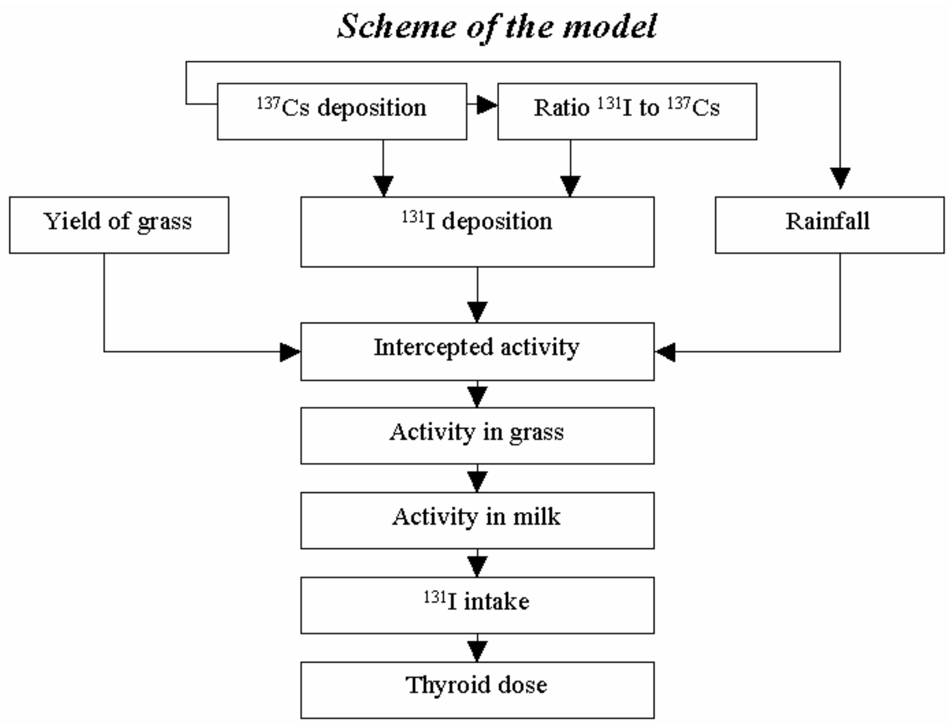

Fig. 2.2. Model to estimate thyroid doses for Belarus after the Chernobyl accident.

Input data

The input quantities for the model are:

- the ^{137}Cs-activity per unit area deposited in a settlement during the Chernobyl accident
- the $^{131}I/^{137}Cs$ ratio per unit area in different regions of Belarus
- a relationship between the rainfall and the ^{137}Cs-activity per unit area
- the start of the grazing period in 1986 in different regions of Belarus.

The ^{137}Cs activity per unit area is available for nearly all settlements of the country. However, data on ^{131}I contamination are very limited. Estimated $^{131}I/^{137}Cs$-ratios are available only for a few locations of Belarus. Beyond that the $^{131}I/^{137}Cs$-ratio varies over a wide range. From the data available the following conclusions were drawn:

- The ^{137}Cs activity per unit area increases with the amount of rainfall during the passage of the cloud. Radionuclides are deposited by both, dry and wet deposition; whereby deposition with rain is more effective.
- In general, the $^{131}I/^{137}Cs$-ratio decreases with increasing ^{137}Cs activities per unit area. Whereas washout of ^{131}I and ^{137}Cs from the near-surface air by rain is about equally effective, the dry deposition of ^{131}I is much more efficient than for ^{137}Cs.
- Therefore, in areas with predominantly dry depositions, activity levels on the ground are relatively low, but the $^{131}I/^{137}Cs$-ratio is high, whereas in areas with predominantly wet depositions, activity levels on the ground are relatively high, but the $^{131}I/^{137}Cs$-ratio is low.

The Chernobyl accident occurred just during the start of the grazing season. Since the consumption of fresh milk is the main pathway, the start of the grazing season has a direct influence on the initial contamination of milk and the ingestion dose to the population affected. According to the available information the grazing season in 1986 started:

- in Brest Oblast and in the Southern part of Gomel Oblast on 25 April
- in Mogilev Oblast and in the Northern part of Gomel Oblast on 26-27 April
- in Minsk and Grodno oblasts on 28-29 April
- in Vitebsk Oblast on 30 April.

Zone division

Based on the information on the rainfall; the ^{131}I /^{137}Cs-ratio in the deposit and the main day of deposition (the day when the ^{131}I activity in daily soil samples reached the maximum), Belarus was divided into five zones with similar radioecological conditions (Fig. 2.3). Within each zone, the deposition mode and the main day of deposition are the same or at least very similar.

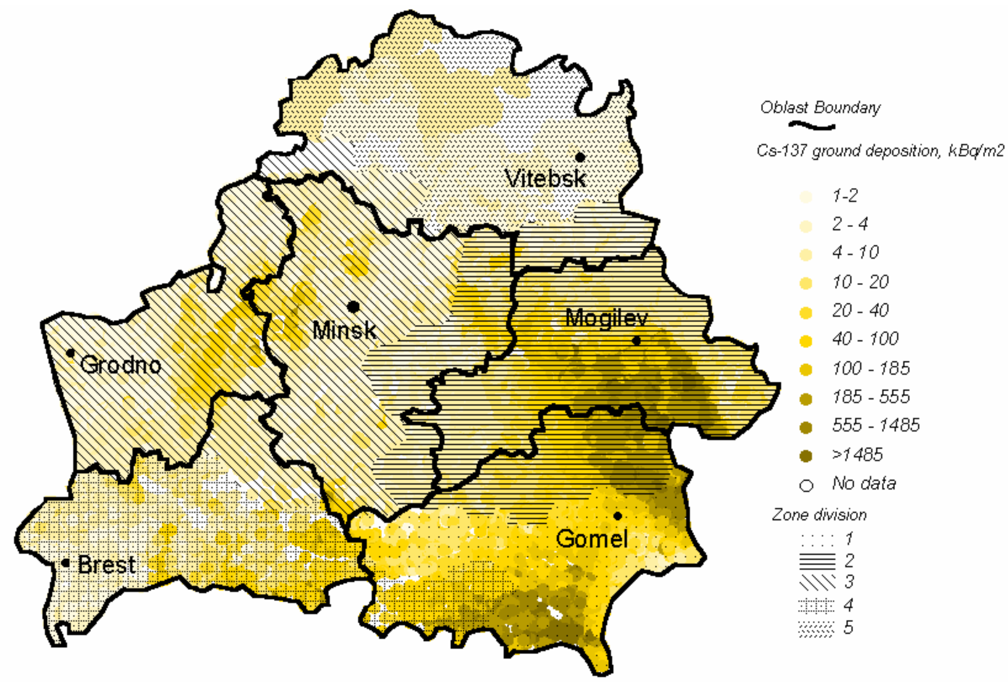

Fig.2.3. Zones of Belarus with similar radioecological conditions.

Thyroid dose estimation

It was assumed that all of the contamination occurred at the day of the main deposition. The rural population was assumed to consume locally produced milk. The levels of ^{131}I in milk that was consumed by the inhabitants of the cities of Belarus were estimated as the average of the milk contamination in the oblast, in which the city is located. For the assessment of the ^{131}I contamination of milk in Minsk City, the average activities in milk from the 36 dairies in Minsk Raion were assumed. For the urban population it was assumed that the consumption of contaminated milk was stopped on 6 May. With the exception of the settlements of the 30km-zone, relocation or evacuation was not taken into account. All other possible countermeasures were not taken into account.

Table 2.9. Thyroid doses for adults as derived from model calculations and from measurements of the ^{131}I activity in the human thyroid.

Oblast	Settlement	Type of settlement	^{137}Cs per unit area (kBq/m^2)	Ratio $^{131}I/^{137}Cs$	Rainfall (mm)	Model dose (Gy)	Monitoring dose (Gy)	Ratio model / monitoring dose
Gomel	Gomel	city	-	-	-	0.11	0.07	1.17
Gomel	Narovlia	town	517	11.72	2.9	0.30	0.22	1.35
Gomel	Vetka	town	751	10.1	4.3	0.19	0.16	1.22
Gomel	Bragin	town	742	10.1	4.2	0.29	0.26	1.11
Gomel	Golubovka	rural	223	16.6	1.2	0.56	0.47	1.19
Gomel	Glazovka	rural	121	8.1	3.8	0.07	0.10	0.66
Gomel	Palmira	rural	495	11.9	2.8	0.50	0.46	1.09
Gomel	Udalevka	rural	241	16.0	1.3	0.55	0.52	1.05
Gomel	Viazhyshe	rural	545	11.5	3.1	0.49	0.51	0.97
Gomel	Vyshemir	rural	207	17.1	1.1	0.57	0.79	0.72
Gomel	Bartolomeevka	rural	1490.	7.6	8.6	0.46	0.45	1.03
Mogilev	Mogilev	city	-	-	-	0.02	0.03	1.51
Mogilev	Cherikov	town	227	6.6	7.3	0.04	0.04	1.02
Mogilev	Pochepy	rural	135	7.8	4.3	0.07	0.05	1.31
Mogilev	Popovka	rural	297	6.1	9.6	0.07	0.03	1.97

RESULTS

Thyroid dose estimates

Average thyroid doses estimated for adults for a number of settlements from different oblasts are summarised in Table 2.9; the underlying data on ^{137}Cs activity per unit area, rainfall and $^{131}I/^{137}Cs$ ratio are given as well. The calculated mean thyroid doses vary from 0.07 to 0.57 Gy.

For a number of settlements, the model results were compared with thyroid dose assessments that were based on measurements of the ^{131}I activity in the human thyroid. For these settlements, the ratios of the predictions based on the radioecological model and on ^{131}I measurements vary in the range from 0.66 to 2, which can be considered as a validation of the model.

The settlement doses were aggregated to obtain estimates of average thyroid doses in the six oblasts of Belarus. The maximum values for thyroid doses are estimated for the inhabitants of the settlements of the Gomel Oblast (Table 2.10). In this oblast, the highest contamination is found. The lowest thyroid doses are estimated for Vitebsk Oblast with the lowest level of deposition. The estimates for Grodno and Minsk areas are very similar. The average thyroid dose for the Mogilev Oblast is similar to Brest Oblast, although the ^{137}Cs-deposition is higher in Mogilev. The reason is the predominantly wet deposition in Mogilev Oblast.

Table 2.10. Average thyroid doses in the Belarusian oblasts as assessed by the radioecological model.

Oblast	Brest	Vitebsk	Gomel	Grodno	Minsk	Mogilev
Dose (Gy)	0.06	0.003	0.32	0.01	0.01	0.07

Uncertainty

For estimating the uncertainty, frequency distributions of the model parameters were estimated and these data were processed by application of Monte Carlo techniques for a settlement in the Gomel region. Parameter distributions were estimated for the ^{137}Cs-activity per unit area, the $^{131}I/^{137}Cs$ ratio, the interception fraction, the daily feed intake of lactating cows, the transfer factor feed-milk and the daily milk intake. For the estimation, the correlations among the parameters are taken into account. However, the correlations coefficients are partly based on judgement since the data for an exact derivation are too poor. Therefore, the correlation coefficients are assumed to quantify a general trend rather than a well-known relationship between two parameters.

The uncertainty of the thyroid exposure is estimated for infants and adults. Due to the underlying distributions of the parameters, the results are close to a log-normal distribution. The uncertainty of the normalised thyroid dose is quantified by the ratio between the 97.5- and 2.5-percentile. The estimated 97.5/2.5-percentile ratio is 23 and 27 for infants and adults, respectively. The uncertainty for adults is somewhat higher due to the wider range of milk intake. The parameter sensitivity declines in the order milk intake, transfer factor feed –milk, interception, $^{131}I/^{137}Cs$ ratio and ^{137}Cs-activity per unit area. Due to the assumed correlations among the last three parameters, their influence on the total uncertainty is quite small.

2.3 DOSE COMPARISONS AND QUALITY CRITERIA FOR THE ECOLOGIC STUDY

DOSE ESTIMATES FOR BELARUS

Age-dependent doses in Belarusian settlements with more than 10 measurements of the ^{131}I activity in the human thyroid have been estimated by FENIX and by GSF by using different methodologies. Both methods are based on the FENIX dose estimates of persons who had their ^{131}I content in the thyroid measured. Otherwise, the methods were independent. The dose estimates of the two methods for the age group 12-14 years agree within a factor of 2 for 98% of settlements (Fig. 2.4).

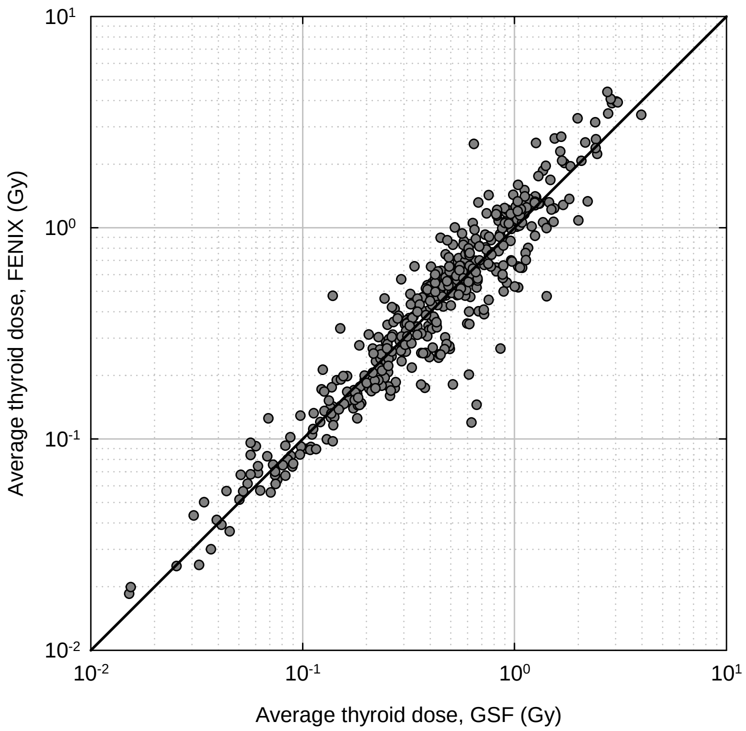

Fig 2.4. Thyroid dose of 12-14 year olds in Belarusian settlements with more then 10 measurements of the ^{131}I activity in the human thyroid as estimated by FENIX and by GSF. Each dot indicates one settlement.

There is also a good agreement of the two methods on the age-dependence of the thyroid dose (Fig. 2.5). A difference is observed, however, for 1-year olds in Minsk.

Two completely different methods have been used to estimate thyroid doses in the oblasts and larger cities of Belarus: FENIX used the measurements of the ^{131}I activity in the human thyroid in the settlements with measurements and the improved semi-empirical model for the other settlements, the other group developed and applied a radioecological model. The two methods agree for the oblasts within a factor of 1.5 (Fig. 2.6). This agreement is surprisingly good.

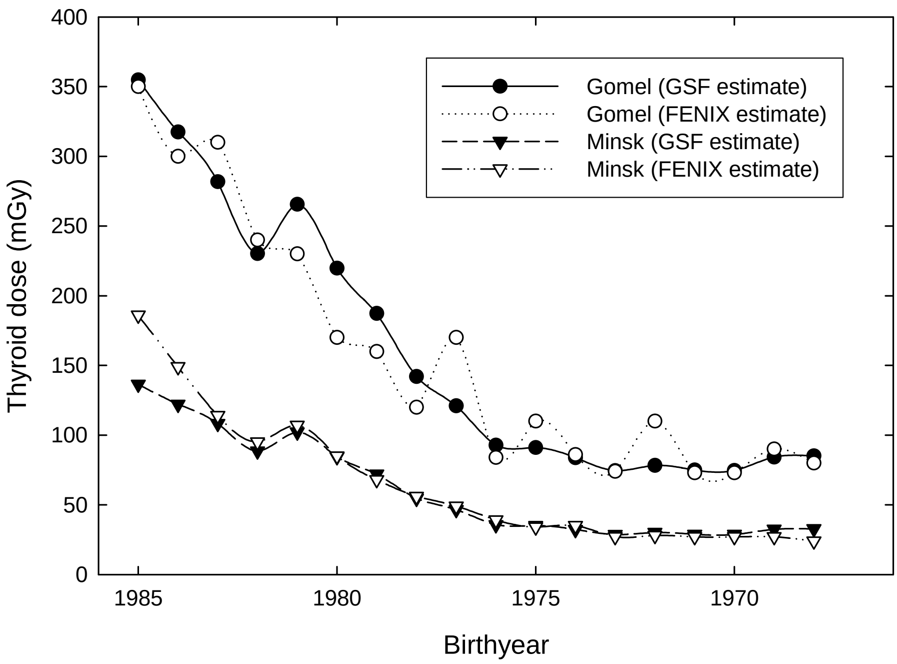

Fig: 2.5 Age-dependent thyroid doses in Gomel City and in Minsk City as obtained by the methods described in Section 2.2.1 (FENIX) and in Section 2.2.2 (GSF).

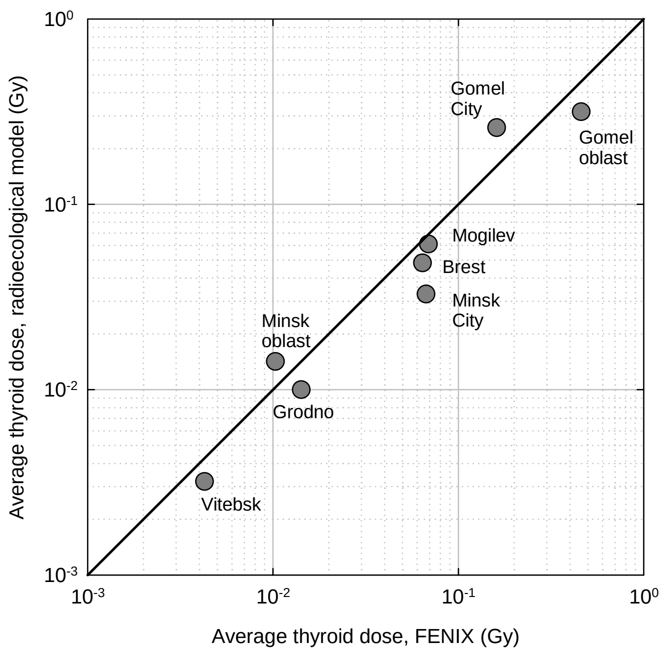

Fig. 2.6 Estimates of average thyroid doses of the birth-year cohort 1968 – 1985 in the Belarusian oblasts and larger cities, as estimated by a radioecological model, and by measurements of the ^{131}I activity in the human thyroid and the semi-empirical model (FENIX).

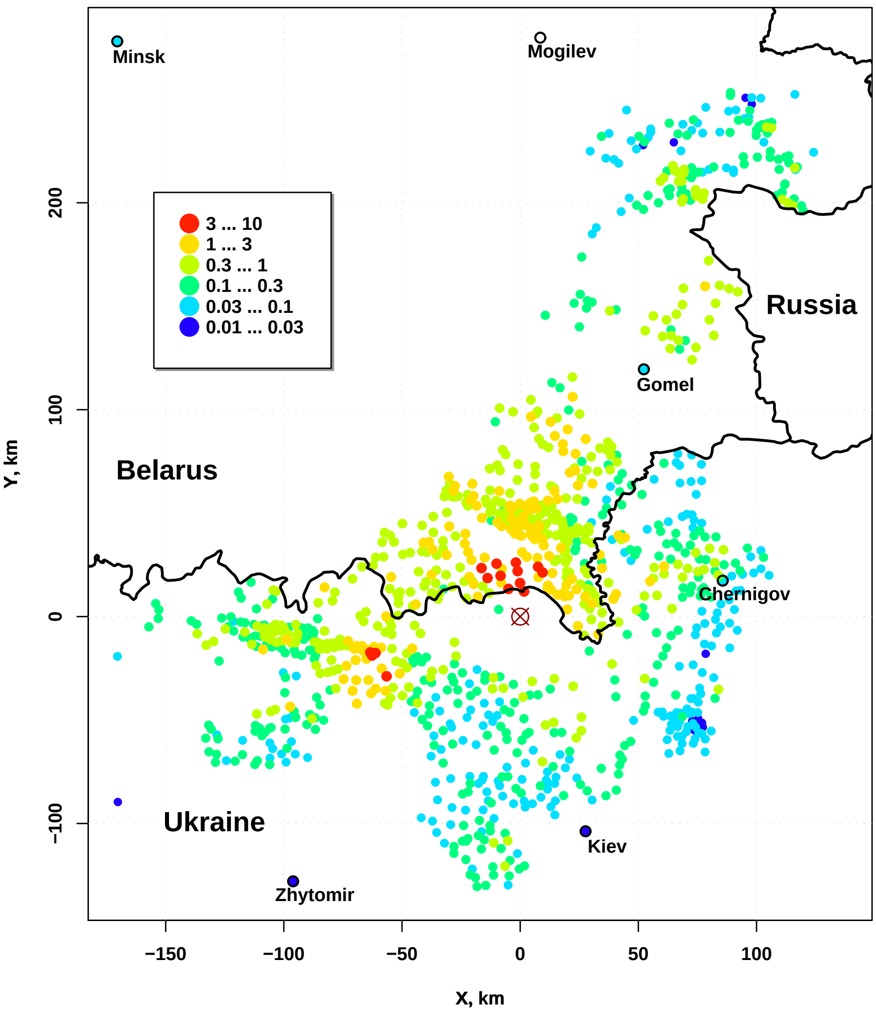

Fig. 2.7. Average thyroid dose (Gy) of the birth cohort 1968 - 85 in 684 Ukrainian and 458 Belarusian settlements, in which more than 10 measurements of the ^{131}I content in the human thyroid have been performed in May/June 1986.

For the cities, however, larger deviations are observed: For Minsk City the dose estimated by the radioecological model is by a factor of 2 higher, for Gomel City by a factor of 1.6 lower. In the settlements, where more than 10 measurements of the ^{131}I activity in the human thyroid are available, dose estimates based on these measurements are considered to be more reliable than dose estimates based on a model.

DOSE ESTIMATES FOR BOTH COUNTRIES

Age-dependent thyroid doses in settlements with more than 10 measurements of the ^{131}I activity in the human thyroid have been estimated completely independently for Ukrainian and for Belarusian settlements. However, results of the two methods agree very well: Settlements at the border of the two countries have similar estimates of thyroid doses (Fig. 2.7).

The distribution of the age- and gender specific doses of the settlements in the two countries is different (Fig. 2.8). The 95% range of the distribution in the Ukrainian settlements is more narrow and shifted to lower doses. The 95% range of average age- and gender specific thyroid doses in the 1142 settlements of the two countries together is 0.017 – 0.69 Gy. The ratio of the two percentiles is 40, for a lognormal distribution this corresponds to a GSD of 2.5.

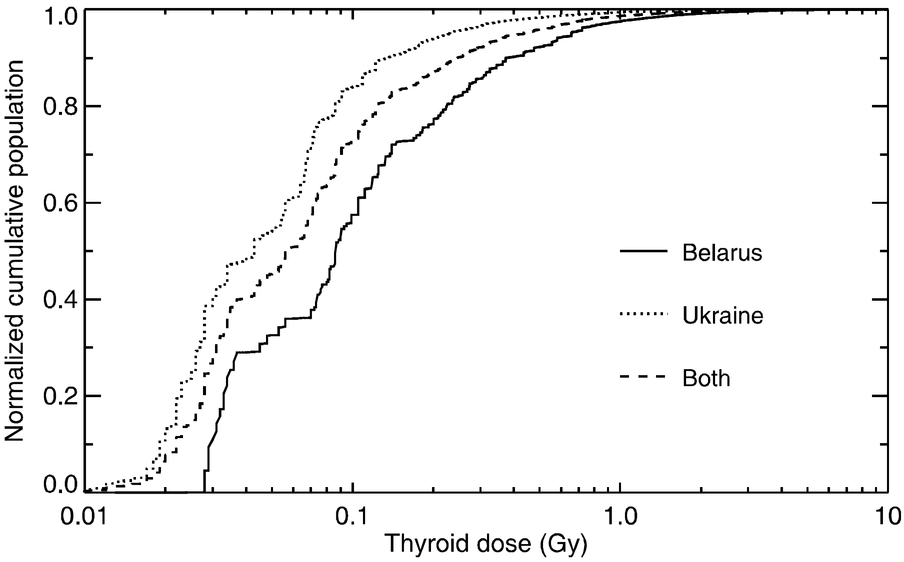

Fig. 2.8. Population weighed distribution of age- and gender specific doses in 684 Ukrainian and 458 Belarusian settlements, in which more than 10 measurements of the ^{131}I content in human thyroids have been performed in May/June 1986.

QUALITY CRITERIA FOR THE ECOLOGIC STUDY

The uncertainty of age-gender specific doses in the single settlements is according to Sections 2.2.2 and 2.4 characterised by a GSD of 1.6.

According to Appendix 1, the GSD of the age- and gender specific relative integral activities varies between 3.3 for 1 year-old girls in towns and 2.1 for 13 years-old boys in villages. The average value of the GSDs is 2.4. This distribution is due to the distribution of the true individual doses within each of the age-gender groups and to the uncertainty of the measurements. It may be concluded that the distribution of individual doses within the ecologic units can be characterised by a GSD smaller than 2.4.

The variability of the average age-gender specific doses in the settlements with more than 10 measurements of the ^{131}I activity in the human thyroid was estimated to be characterised by a GSD of 2.5 (see above).

According to these estimates, two criteria for a reliable ecologic study are fulfilled: The variability of the average doses for the ecologic units (GSD = 2.5) is

- considerably larger than the uncertainty of the average doses (GSD = 1.6)
- larger than the variability of the individual doses within the ecologic units (GSD < 2.4).

The difference of the 95 percentile and the 5 percentile of the distribution of the age- and gender-dependent doses in the 1142 study settlements is 0.4 Gy (Fig. 2.8). Assuming an excess relative risk per dose of 10 Gy^{-1}, the incidence in the upper dose group is expected to be by a factor of five larger then in the lower dose group. Thus other risk factors play compared to the radiation a negligible role.

2.4 SPATIAL INTERPOLATION

As shown in the previous sections, models can be quite useful for the general evaluation of thyroid exposures in the whole country of Belarus due to the Chernobyl accident. Due to large uncertainties, however, models are less suited for analyses of excess risks. It is therefore explored in the present Section, whether a spatial interpolation of the results for settlements with more than 10 measurements of the ^{131}I activity in the human thyroid may be applied for an extension of the study area. Approaches studied here base on geostatistical methods originating from geology and mining. The methods provide a way to interpolate spatial data taking into account observed spatial correlations between the data points.

This Section is a summary of more extensive reports in Appendices 5 and 6.

MATERIALS AND METHODS

Description of the data

The spatial analysis is conducted for 593 settlements in Ukraine, 308 settlements located in the South-Eastern part of Bealrus, and 152 settlements located in the Northern part of Gomel Oblast and the South-Eastern part of Mogilev Oblast (see also Fig. 2.7). These settlements, in which more than 10 measurements of ^{131}I activity in the human thyroid have been performed in May/June 1986, are called sample settlements. For an interpolation of the thyroid doses in total 1227 (target) settlements were considered, which had a maximal distance of 30 km from any of the sample settlements.

The data for the sample settlements j in Ukraine were gender-dependent integrated ^{131}I activities $\tilde{Q}_{ref,s,j}$ for the reference age group of 12–14 years (Section 2.1). For the purpose of the present study, these data were averaged between genders.

For Belarus, the average integrated activity G_{Wj} in the thyroid for the age-group 1-18 years in rural settlements (Section 2.2.2) was used. The average value of the function f_a in the range of 12 to 14 years is 1.15. The Belarusian data were multiplied by this factor in order to make the Belarusian data compatible with the Ukrainian data.

Basic quantities and equations

The sample data, $\tilde{Q}_{ref,j}$ are considered as realizations of a spatial random process, $\hat{Q}(x)$, in the sample points x_j, where x_j are two-dimensional vectors. Because of an apparent log-normality, transformed data $\tilde{S}_j = \ln(\tilde{Q}_{ref,j})$ are considered as realizations of a Gaussian spatial process $\hat{S}(x) = \ln(\hat{Q}(x))$.

The sample data demonstrate both, systematic behavior and random fluctuations, thus the following model of the random process is assumed

$$\hat{S}(x) = m(x) + Z(x) = m(x) + Y(x) + \varepsilon , \qquad (2.14)$$

where $m(x)$, the “trend”, represents the non-stochastic spatial component of the random process $\hat{S}(x)$; $Z(x)$ is a stochastic part of the process, which can be separated into correlated and non-correlated components, $Y(x)$ and ε, respectively. The variance of the non-correlated component, $\mathrm{var}(\varepsilon) = \tau^2$, is called *nugget* in the geostatistical literature and can be interpreted as a combined result of micro-scale variations and a measurement error.

A two-stage interpolation procedure was developed. At the first stage, an attempt is made to reconstruct a spatial trend $m(x)$ using the Loess technique of local spatial regression on sample points (Cleveland and Grosse 1991). Then, residuals are analyzed and found to be spatially correlated, and classical kriging methods (Webster and Oliver 2001) are used to predict values for the target settlements.

Preferential sampling in Belarus and feasibility study

In the contaminated areas, there was a possible selection of settlements for measurements of the ^{131}I activity in the human thyroid according to the cesium contamination. A preferential sampling may introduce an overestimation of doses in target settlements which are obtained by interpolation from sample settlements. A feasibility study has been performed to explore whether there is a possibility to interpolate data in spite of a possible preferential sampling in Belarus. The feasibility study was conducted with data on the ^{137}Cs activity per unit area, which is known for the sample and for the target settlements. These data provide a possibility to develop and to validate a method to compensate for a bias caused by preferential sampling.

In the feasibility study, the 460 Belarusian sample settlements were split into two spatial groups. Group A consists of 308 settlements in the South-Eastern part of Belarus, close to the Chernobyl power plant, group B comprises the remaining settlements located in the Northern

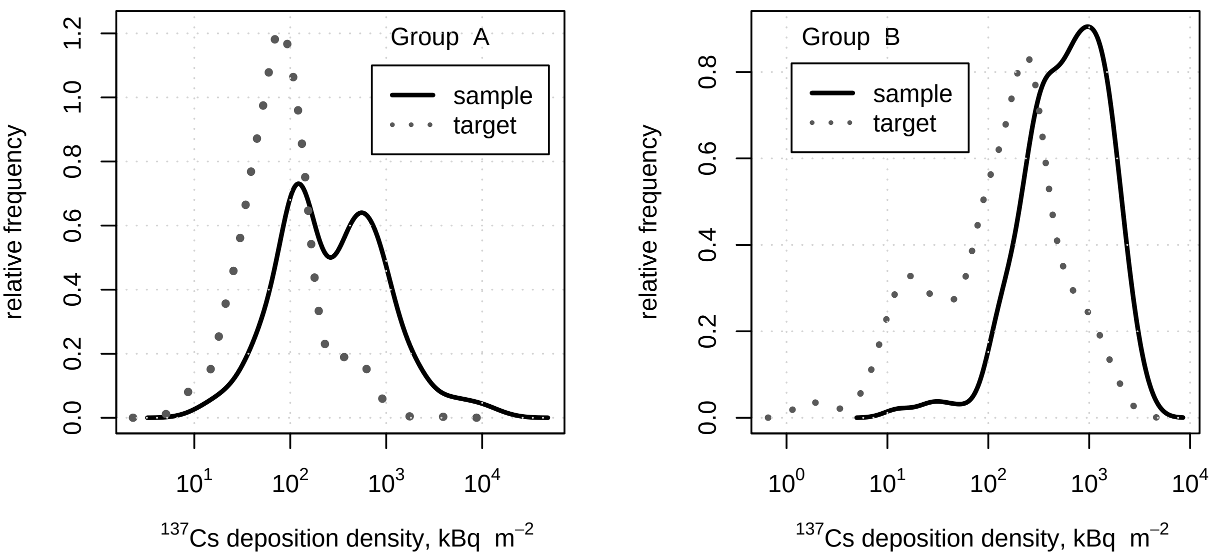

Fig. 2.9. Relative frequency (smoothed) of sample and target settlements in dependence on the ^{137}Cs deposition density for the South-Eastern part of Belarus, close to the Chernobyl power plant (group A) and for the Northern part of Gomel Oblast and the South-Eastern part of Mogilev Oblast (group B).

part of Gomel Oblast and the South-Eastern part of Mogilev Oblast (see also Fig. 2.7). For both groups, the frequency distributions of the ^{137}Cs activities per unit area in the sample settlements are shifted to higher values than in the target settlements (Fig. 2.9). Lower values are to be expected for the target settlements, because part of them is located at the boundaries of the high dose spots. However, the nearly cut-off like behavior of the distribution for sample settlements in group B at 100 kBq m^{-2} and the high frequency of target settlements with ^{137}Cs activities per unit area in the range of 10 - 100 kBq m^{-2} indicate that there was also a preferential sampling within the highly contaminated areas.

RESULTS

Feasibility study

The feasibility study was performed for different ranges of distances of the target settlements from the next sample settlement. For a range of up to 15 km, there were 351 target settlements for group A sample settlements in Belarus. There was a good agreement of the predicted ^{137}Cs activity per unit area in the target settlements with the measured activities (Fig. 2.10).

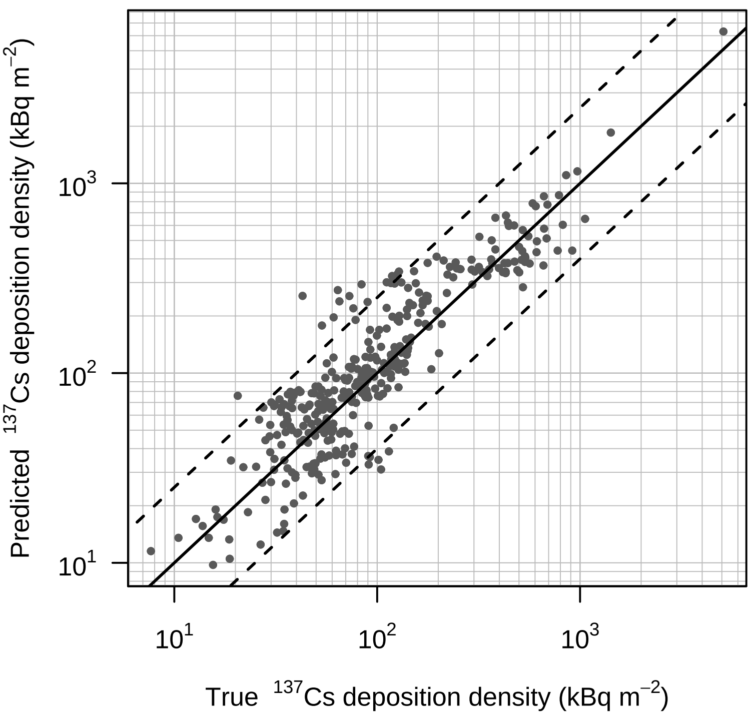

Fig. 2.10. ^{137}Cs activity per unit area in 351 target settlements for the sample settlements of group A: Measured (true) and predicted (by interpolation based on a trend model) value. The solid line indicates the line of identical results, the broken lines an uncertainty range as it is typical for thyroid dose assessments in the sample settlements (Section 2.2.2).

The objective of the feasibility study was to explore, whether thyroid dose assessments for the sample settlements can be extrapolated to the target settlements. The uncertainty of the age-specific thyroid dose in the sample settlement has been estimated to correspond to a GSD of 1.6 (Section 2.2.2). A corresponding 95% confidence interval has been indicated in Fig 2.10. The ^{137}Cs values predicted for 331 of the 351 target settlements (or 94%) are within this range, indicating that the predicted thyroid doses in the target settlements can be expected to have not a considerably larger uncertainty then the thyroid dose estimates in the sample settlements.

Results for the target settlements of group B sample settlements in Belarus are less satisfactory. Reasons are the less dense spatial distribution of the sample settlements and a higher spatial variability of the ^{137}Cs activity per unit area. The latter is due to the heterogeneous distribution of the wet deposition in the area of group B settlements. It can be expected that the thyroid doses show less variability, because high depositions with larger precipitations were partly compensated in thyroid dose due to a lower retention of the ^{131}I on the grass (Section 2.2.3).

Spatial variability of age-specific thyroid doses in sample settlements

The variogram of the sample data $\tilde{S}_j$ for the Ukrainian and Belarusian (group A) settlements shows - as to be expected - long range correlations (upper curve in Fig. 2.11). The local regression method of LOESS method has been used to derive a spatial trend $m(x)$. The resulting trend function has a maximum in Belarus close to the Chernobyl reactor site, decreases fast in the South-East direction and more slowly in Western and Northern directions (Fig 2.12).

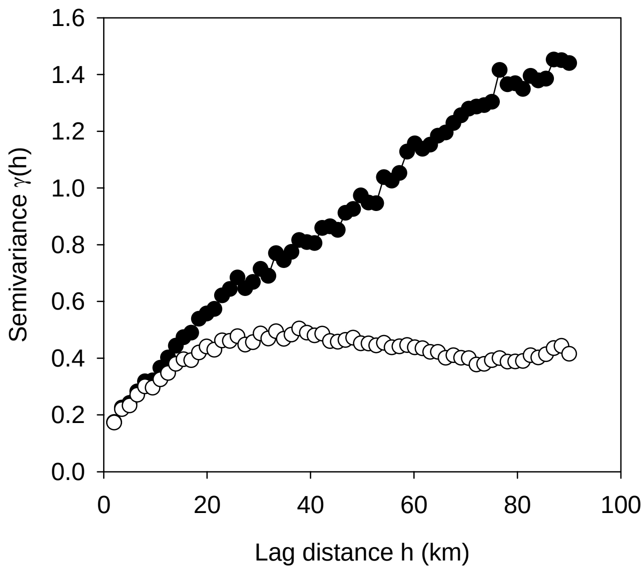

Fig. 2.11. Variograms for the logarithm of the integrated activity in Ukrainian and Belarusian (group A) sample settlements (black circles) and for the residuals after subtraction of the trend $m(x)$ in Fig. 2.12.

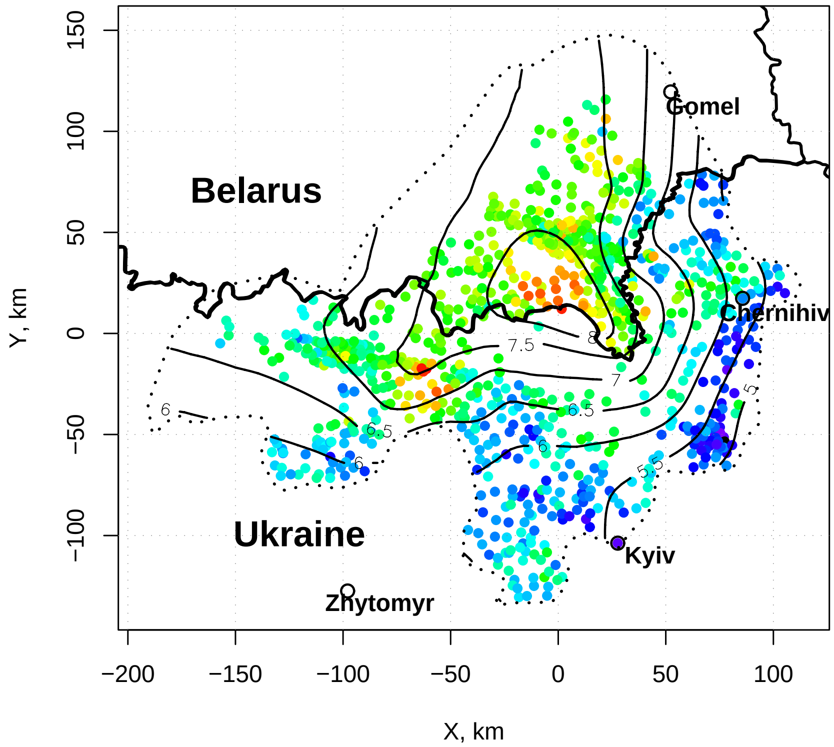

Fig. 2.12. Isolines of the trend function $m(x)$ for the logarithm of the integrated activity in Ukrainian and Belarusian (group A) sample settlements.

The variance of the residuals increases for small distances between sample settlements up to 17 km and has a plateau for larger distances (Fig. 2.11). The nugget is equal to 0.15; corresponding to a GSD of the integrated activities of 1.5. This is a rough measure for the uncertainty of the thyroid dose estimates. The nugget deviates from the uncertainty of the sample values in two respects: Micro-scale variations make it larger, and correlations between the sample values in adjacent settlements smaller.

Cross-validation and integrated activities in target settlements

The *kriging* method is applied to the variogram for the residuals for calculating best estimates and uncertainties of the age-specific integrated ^{131}I activity in the human thyroid in the target settlements. By construction, the variance of the predicted values lies in the range of the nugget and the plateau value in the variogram.

Before applying the method to the target settlements, a cross-validation by the “leaving-one-out” method has been performed: The method based on all sample settlements except one is applied to predict the integrated activity in the left-out sample settlement. In the exercise, the prediction for 837 left-out settlements (93% of the 901 sample settlements) lie within a factor of 2.5-range of the original integrated activity value. This indicates that the uncertainty of the predicted value is comparable to the uncertainty of the sample values (Fig. 2.13). The geometric mean of the ratios of predicted and sample values is 1.09. This systematic bias is small compared to the uncertainty of the estimates of integrated activities in the sample settlements. On the other hand, there is a systematic overestimation of small doses and underestimation of high doses, which would lead to a bias in a risk analysis that is based on interpolated data. Figure 2.14 shows integrated activities in the sample and in the target settlements.

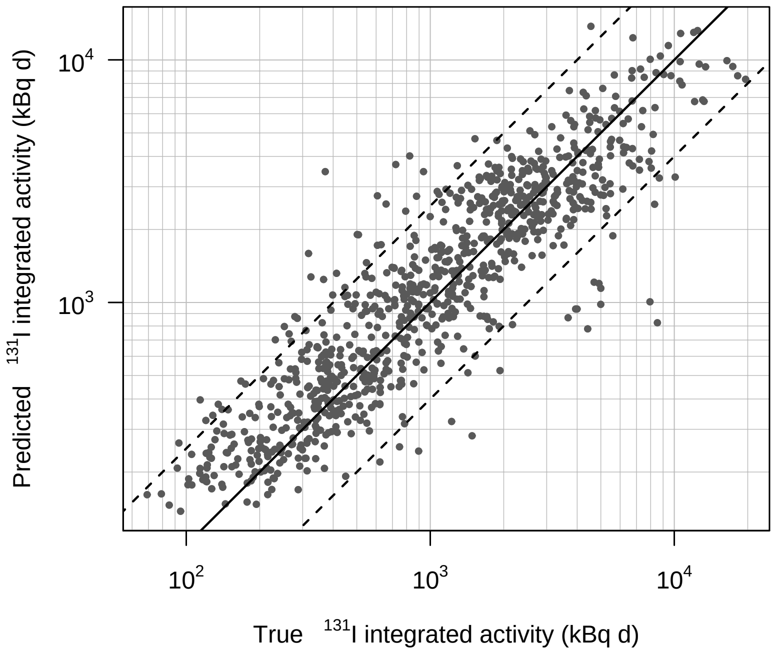

Fig. 2.13. Results of the "leaving-one-out" cross-validation. Predicted values in the sample points vs. sample data. The dashed lines indicate the uncertainty range of the 'true' sample values.

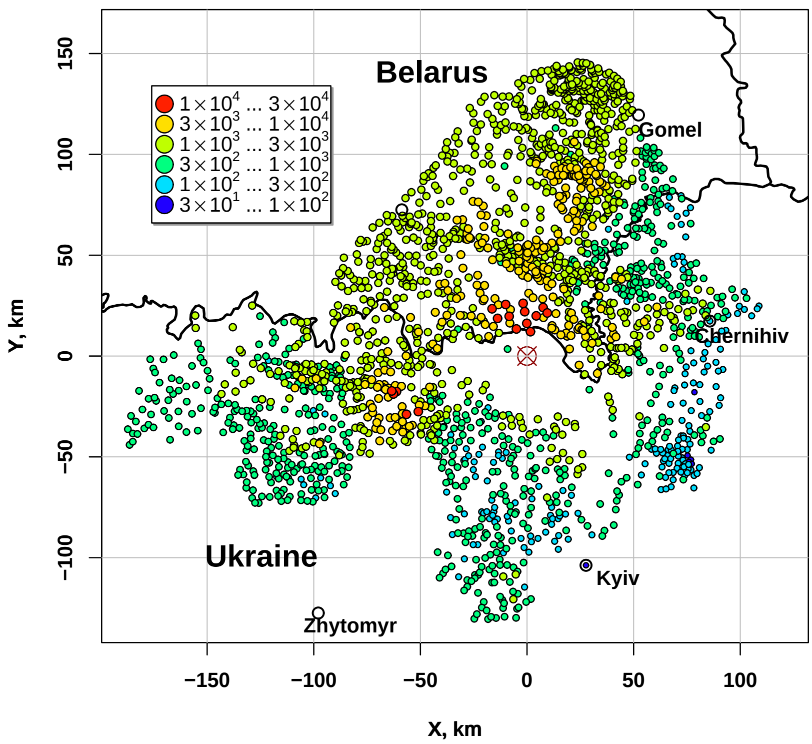

Fig. 2.14. Integrated activities (kBq day) of 12-14 year old in 901 sample and 1227 target settlements.

3. THYROID CANCER DATA

3.1 UKRAINE

It is the objective of this Section to analyse

- the number and incidence of thyroid cancer in persons who were aged 0 to 18 years in Ukraine at the time of the Chernobyl accident
- morphological characteristics of carcinomas in this category of patients.

Stastistical and morphological data on the thyroid cancer cases in Ukraine, as they were available before the start of the project have been published by Tronko et al. (1999).

This Section is a summary of the more extensive report in Appendix 7.

MATERIALS AND METHODS

The data have been obtained from the clinico-morphological Register of the Institute of Endocrinology and Metabolism of the Academy of Medical Sciences of Ukraine. This Register has been established in 1992 on the base of statistical reports on the number of thyroid cancer cases in subjects in the birth-year cohorts 1968 - 1986 in all 27 regions of Ukraine, and on a review of medical records of patients having undergone surgical or postoperative treatment at the Hospital of the Institute of Endocrinology and Metabolism of the Academy of Medical Sciences of Ukraine.

Since at the start of the project the birth year but not the exact birth date was known for all patients, the difference between 1986 and birth year was used as a surrogate for age, *i.e.*, 0 to 18 years at the time of the accident in the text stands for birth years 1986 to 1968, and, *e.g.*, 4 to 14 years at the time of surgery in 1990 stands for birth years 1986 to 1976.

Histological analyses of carcinomas have been performed after surgical treatment of thyroid cancer patients at the Institute of Endocrinology and Metabolism, or of material (paraffin blocks, histological specimens) forwarded to the Laboratory of Morphology of the Institute for consultative conclusion. The patients were operated in the period 1990 - 2002. Most of the cases have been additionally studied by international experts. The diagnosis of carcinoma has been confirmed in all the cases under study.

The number and the incidence rate of thyroid cancer cases operated in the period 1986 – 2002 have been calculated of different groups of age at the time of the accident or at the time of surgery. A comparison was made of the incidence rate for 6 regions of Ukraine being the most contaminated by iodine radionuclides (Kyiv, Chernihiv, Zhytomyr, Rovno and Cherkassy oblasts, and Kyiv City) and the other 21 regions of Ukraine.

A morphological analysis has been performed for 3 age groups at the time of surgery (children aged from 4 to 14, adolescents aged from 15 to 18, and young adults aged from 19 to 34) for patients born in 1968 - 1985 and for the 3 calendar-year periods (1990 - 1995, 1996 - 2001, and 2002). Morphological types, size, extrathyroid spreading and presence of regional metastases have been analysed. Similar analyses have been performed separately for children born in 1986, and born in 1987 or later.

RESULTS

Number of thyroid cancer cases and incidence rates

Dependencies on age at exposure. For the post-Chernobyl period (1986-2002), 2674 cases of thyroid cancer in patients born in 1968-1986 have been reported; among them 1887 were children during the accident, and 787 were adolescents (Table 3.1). Including 62 cases reported in children born after 1986, the Register comprises 2736 cases of thyroid carcinomas operated in the period 1986 – 2002.

Table 3.1 Number of annual thyroid cancer cases in Ukraine for different groups of age at the time of the accident.

Year of surgery	Females			Males			Both		
	0-14	15-18	0-18	0-14	15-18	0-18	0-14	15-18	0-18
1986	4	9	13	4	2	6	8	11	19
1987	9	8	17	2	6	8	11	14	25
1988	7	9	16	4	2	6	11	11	22
1989	17	9	26	7	4	11	24	13	37
1990	25	19	44	17	1	18	42	20	62
1991	31	19	50	15	4	19	46	23	69
1992	57	26	83	26	9	35	83	35	118
1993	53	39	92	30	7	37	83	46	129
1994	76	34	110	28	9	37	104	43	147
1995	87	58	145	30	8	38	117	66	183
1996	97	44	141	41	10	51	138	54	192
1997	106	50	156	30	11	41	136	61	197
1998	133	69	202	37	12	49	170	81	251
1999	158	59	217	59	8	67	217	67	284
2000	143	56	199	37	13	50	180	69	249
2001	219	72	291	55	13	68	274	85	359
2002	193	66	259	50	22	72	243	88	331

The number of thyroid cancer cases increased with time after the accident. The increase was most pronounced in those who were children at the time of the Chernobyl accident. The ratio of female to male cases increased with age at the time of accident: from 3 (1415 to 472 cases) for children to 4.6 (646 to 141 cases) for adolescents. It was 2 (41 to 21 cases) for those born after 1986.

In the period 1986 - 1989, the thyroid cancer incidence rate for children at the time of the accident was 0.12 cases per 10^5 personyears (PY). In 1990 - 1995 it has increased by a factor of 6 (0.7 cases per 10^5 PY), in 1996 - 2001 by a factor of 14 (1.7 cases per 10^5 PY), and in 2002 by a factor of 18 (2.2 cases per 10^5 PY). Part of this increase is due to the aging of the cohort. However, the increase in the incidence rate is much more expressed in the 6 most contaminated regions of Ukraine, indicating the strong influence of the Chernobyl accident.

The incidence rate of malignant thyroid tumours among adolescents at the time of the Chernobyl accident increased less, from 0.45 cases per 10^5 PY in 1986 - 1989, to 1.4 cases per 10^5 PY in 1990 - 1995, and 2.5 cases per 10^5 PY in 1996 - 2001. In 2002, the incidence rate among adolescents at the time of the accident was 3.2, exceeding the rate for 1986 - 1989 by a factor of 7.

Dependencies on age at surgery. By their age at surgery, the cases in the birth cohort 1968 - 1986 were distributed as follows: 448 were children aged 0 to 14 (292 females (F), 156 males (M); with a female to male ratio F:M=1.9); 468 were adolescents aged 15 to 18 (326 F, 142 M; F:M=2.3), and 1758 were young adults aged 19 to 34 years (1443 F, 315 M; F:M=4.6). The ratio of female to male cases increased with age at the time of surgery.

The rate of growth of the incidence with time after exposure was highest in children having been operated at the age up to 15 years, and such a growth was reported beginning from 1990. The incidence in children who were exposed following the Chernobyl accident (born before 1987) was highest in 1998 - 2000. In non-exposed children (born in 1987 or later) the average incidence rate in the age-at-surgery group 0 to 14 years for the period 1995–2001 was similar to the level of the exposed in 1986 - 1989. In the group of exposed children, there is during the period 1990 - 2000 a marked difference in incidence between the 6 contaminated and the 21 less contaminated regions. In non-exposed children there was no significant difference in incidence between the 6 and 21 regions before 2000. But, it should be stressed that such a difference was observed in 2001-2002, which needs further analysis.

A significant increase of the incidence of malignant thyroid tumours among started not before 1994. The difference between the incidence rates of adolescents in the 6 and 21 regions increased with time elapsed after the accident.

The incidence rate of young adults at the time of surgery (older than 18 among the birth-year cohort 1968 - 1986) increased in the whole of Ukraine from 0.55 cases per 10^5 PY in 1987 - 1989, by a factor of 1.9 (1.0 cases per 10^5 PY) in 1990 - 1995, and by a factor of 3.7 (2.1 cases per 105 PY) for the period 1996 - 2001. In 2002, the incidence rate was by a factor 4.6 (2.6 cases per 10^5 PY). The difference between the incidence rates in the 6 and 21 regions is lower than for children and adolescents, and starts to be more significant in 1998.

Morphological analyses

<u>*Histological types for birth cohort 1968 - 1985*</u>. In all age groups for the birth cohort 1968 - 1985 and for all periods of observation, more than 92% of the cases are papillary carcinomas (Table 3.2). There is an increase of the percentage of follicular carcinoma from 3% in 1990 - 1995 to 6% in 2002. Follicular carcinomas were bigger than papillary ones. In spite of a larger size, follicular carcinomas were represented by less aggressive tumours: only one widely invasive case with size 5.2 cm was associated with extrathyroid spreading and lymph nodes metastases.

Table 3.2. Histological types of thyroid carcinoma in patients who were born in 1968 – 1985 (1009 cases for the period 1990 – 2002). Each cell gives the number of cases; the percentage is added in parentheses for both genders together.

Period of surgery	Gender	Histological type of carcinoma*			
		Papillary	Follicular	Medullary	Anaplastic
1990 – 1995	females	144	3	7	1
	males	73	4	1	1
	both	217 (92.7%)	7 (3.0%)	8 (3.4%)	2 (0.9%)
1996 – 2001	females	432	20	4	-
	males	148	6	2	-
	both	580 (94.8%)	26 (4.2%)	6 (1.0%)	-
2002	females	112	9	3	-
	males	36	1	2	-
	both	148 (90.8%)	10 (6.1%)	5 (3.1%)	-
1990 – 2002	females	688	32	14	1
	males	257	11	5	1
	both	945 (93.7%)	43 (4.3%)	19 (1.9%)	2 (0.2%)

*: Oxyphillic cell carcinoma have not been observed.

Size of papillary carcinomas. For all age groups and all periods of observation, papillary carcinomas from 1 to 3 cm in diameter were dominant (Table 3.3). At the same time, it should be noted that the percentage of "small" carcinomas (size 10 mm or less) was increasing with time after the accident, while the percentage of larger tumours (> 3 cm) was decreasing.

Table 3.3. Size of papillary thyroid carcinomas in patients who were born in 1968 – 1985. Given are the numbers of cases and (in parentheses) the percentages.

Size of tumour (cm)	Period of surgery			
	1990 – 1995	1996 – 2001	2002	1990 - 2002
≤ 1.0	8 (4%)	49 (12%)	20 (20%)	77 (11%)
1.1 – 2.0	69 (35%)	198 (48%)	38 (39%)	305 (43%)
2.1 – 3.0	56 (29%)	62 (15%)	20 (20%)	138 (19%)
3.1 – 4.0	23 (12%)	41 (10%)	8 (8%)	72 (10%)
4.1 – 5.0	22 (11%)	35 (8%)	5 (5%)	62 (9%)
5.1 – 6.0	11 (6%)	17 (4%)	5 (5%)	33 (5%)
> 6.0	7 (4%)	14 (3%)	2 (2%)	23 (3%)
All	196 (100 %)	416 (100%)	98 (100%)	710 (100%)

Extrathyroidal spreading. Extrathyroidal spreading was reported for 44% of the papillary tumours. For any size of tumours, extrathyroidal spreading of carcinomas (T4 category by TNM classification) was more often reported for children than for adolescents and young adults. The percentage of papillary carcinoma with extrathyroidal spreading decreased with time elapsed after the accident for any size of tumour.

Regional metastases. Regional metastases were reported for 50% of the tumours. The highest percentage of regional metastases was observed in children, and the lowest in young adults. The percentage of regional metastases decreased with time elapsed after the accident for any size of tumour (Table 3.4).

Table 3.3. Percentage of papillary thyroid carcinomas with extra-thyroid spreading (T4-category of TNM classification) in patients who were born in 1968 – 1985 (710 cases for the period 1990 - 2002).

Size of tumour (cm)	Period of surgery			
	1990 – 1995	1996 – 2001	2002	1990 - 2002
≤ 1.0	13%	16%	10%	14%
1.1 – 2.0	58%	37%	26%	41%
2.1 – 3.0	59%	44%	35%	49%
3.1 – 4.0	65%	56%	25%	56%
4.1 – 5.0	82%	34%	40%	52%
5.1 – 6.0	64%	88%	20%	70%
> 6.0	86%	64%	50%	70%
All	61%	40%	26%	44%

Table 3.4. Percentage of tumours with regional metastases (N1a,b - category of TNM classification) in patients who were born in 1968 – 1985 (710 cases for the period 1990 - 2002).

Size of tumour (cm)	Period of surgery			
	1990 – 1995	1996 – 2001	2002	1990 - 2002
≤ 1.0	13%	18%	20%	18%
1.1 – 2.0	54%	48%	32%	47%
2.1 – 3.0	55%	47%	35%	49%
3.1 – 4.0	61%	63%	50%	63%
4.1 – 5.0	68%	66%	60%	66%
5.1 – 6.0	82%	94%	40%	82%
> 6.0	86%	71%	50%	74%
All	58%	50%	34%	50%

Morphological classification of carcinomas among the birth cohorts 1986 and later. For persons born in 1986, and for those born later, papillary carcinomas are dominant, however, with a lower frequency than for the birth-year cohort 1968 – 85 (Table 3.5). For those born in 1987 or later, the percentage of follicular tumours is higher than for the exposed. However, this observation is based on a small number (8) of cases.

Table 3.5. Histological types of thyroid carcinoma in patients who were born in 1986 (41 cases for the period 1990 – 2002) or later (57 cases for the period 1995 – 2002). Each cell gives the number of cases; for both genders the percentage is added in parentheses.

Birth cohort	Gender	Histological type of carcinoma*			
		Papillary	Follicular	Medullary	Oxyphillic cell
1986	females	20	1	2	-
	males	15	2	-	1
	both	35 (85%)	3 (7%)	2 (5%)	1 (2%)
1987 – 2002	females	27	7	2	-
	males	18	1	2	-
	both	45 (79%)	8 (14%)	4 (7%)	-

*: Anaplastic carcinoma have not been observed.

The papillary carcinomas for those born in 1986 have similar signs of extrathyroidal spreading and of presence of regional metastases as the birth-year cohort 1968 – 1985. In subjects born in 1987 and later, papillary carcinomas are associated with high invasive features in the presence of a primary focus measuring more than 1 cm. “Small” tumours up to 1 cm in this age group did not manifest lymphoid metastatic spreading. Such a comparison has a preliminary character and needs further analysis in the process of data collection.

3.2 BELARUS

The objective of the present Section is to give

- a presentation of time, age and gender dependencies of thyroid cancer cases after the Chernobyl accident among those born in 1968 or later in Belarus
- a pathological classification of these thyroid malignancies and
- a comparison with spontaneous thyroid carcinomas.

This Section is a summary of more extensive reports in Appendices 8 and 9.

MATERIALS AND METHODS

Thyroid cancer cases

A register of exposed thyroid cancer patients has been formed in the Thyroid Cancer Center of the Belarusian Medical University. Cross-checks are performed with the Belarusian Cancer Registry and the Belarusian State Chernobyl Registry. In addition, the information was verified through indirect interview of patients with thyroid cancer by sending them specific questionnaires. Response to these questionnaires has allowed for quality control and quality assurance of individual information.

The data sets include birth date, gender, place of residence in Belarus at the time of the accident, date of surgery and other clinical information. In addition to the exposed people (0 - 18 years at the time of the accident), there is a second group of patients, who were born after 1986. Being not exposed, they were considered as spontaneous (sporadic) cases. All cases of the second group received therapy in the Thyroid Cancer Center. Thyroid cancer cases operated in the period 1986 - 2002 were analysed.

The majority of cases of exposed people underwent a revised pathological assessment including an international review. The spread of the tumours and cancer pathology were categorised according to the TNM UICC and WHO pathological classification (see Annex 1 of Appendix 8).

Population data

The gender-age structure of the population in 1986 has been derived by the following algorithm:

- The algorithm is based on the gender-age structure of the population of the six oblasts (regions) and two larger cities (Minsk and Gomel) of Belarus as given in the census data for 1989
- The gender-age structure in 1989 in the settlements was derived from the total number of inhabitants in 1989 under the assumption that all settlements in an oblast have the same gender-age structure
- The gender-age structure in 1986 was derived applying gender-age specific death-rates in 1986 - 1988.

The results showed a good agreement with statistical reports of the Ministry of Health of the Belarusian SSR.

RESULTS

Thyroid cancer cases and incidence rate

The thyroid cancer registry contains records on 1956 cases in the period 1 June 1986 to 31 December 2002. Among those aged 0-18 at the time of the accident, there were 1916 cases, among the unexposed there were 40 cases in the birth-year groups 1987 – 1994. Most of the exposed individuals with thyroid cancer lived in Gomel and Brest oblasts (high exposures), most of the unexposed in Minsk City (large population).

Since 1990, a significant increase of the thyroid cancer incidence has been observed among those aged 0-18 at the time of the accident (Fig. 3.1). The steep increase continued until 1994. Since then, the already high incidence rate continues to increase further, but with a smaller slope. There is no clear increase of thyroid carcinomas cases before the year 2000 among those born after 1986. Subsequently, a moderate increase is also observed in this group, especially for females.

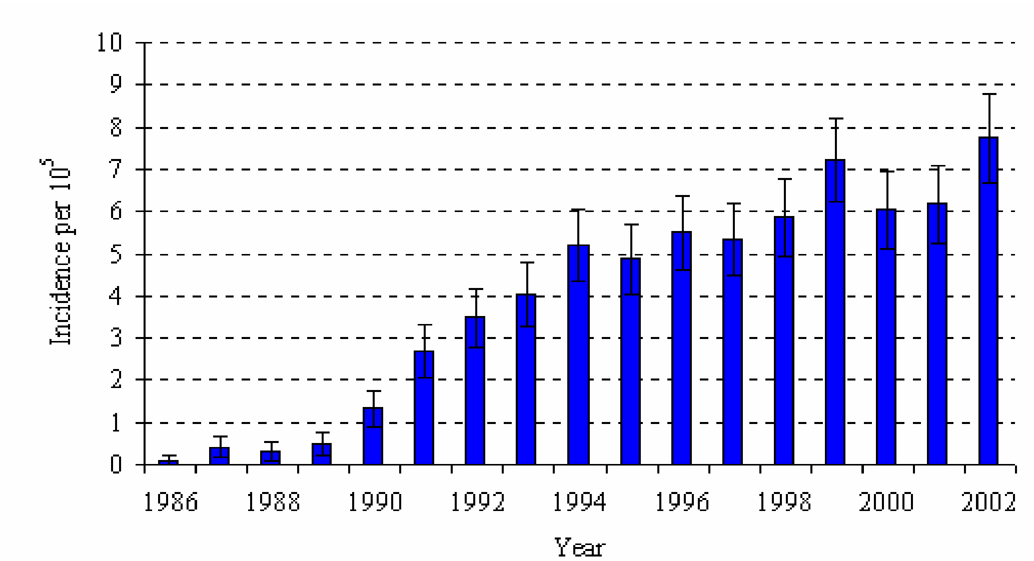

Fig.3.1. Thyroid cancer incidence rate in Belarus among those aged 0-18 at the time of the accident.

About twice as much thyroid cancer cases are observed for females compared to males (Table 3.6). There is no significant sign of a change of this ratio with time after exposure. The number of thyroid cancer cases among those born in 1986 was 71, 68% of them were born before the accident (Table 3.7).

Table 3.6. Number of thyroid cancer cases and incidence rate among those aged 0-18 at the time of the accident.
.

Year	Cases			Incidence rate per 10^5 PY			female/male ratio
	Females	Males	Both	Females	Males	Both	
1986	2	1	3	0.14	0.07	0.10	2.0
1987	9	3	12	0.63	0.21	0.42	3.0
1988	5	4	9	0.35	0.28	0.31	1.3
1989	9	5	14	0.63	0.35	0.49	1.8
1990	19	19	38	1.33	1.32	1.33	1.0
1991	54	23	77	3.79	1.59	2.69	2.4
1992	56	44	100	3.93	3.05	3.49	1.3
1993	88	28	116	6.18	1.94	4.05	3.2
1994	101	48	149	7.09	3.33	5.20	2.1
1995	92	48	140	6.46	3.33	4.88	1.9
1996	114	44	158	8.00	3.05	5.51	2.6
1997	104	49	153	7.30	3.40	5.34	2.1
1998	115	53	168	8.07	3.67	5.86	2.2
1999	139	68	207	9.75	4.71	7.22	2.1
2000	120	53	173	8.42	3.67	6.03	2.3
2001	120	57	177	8.42	3.95	6.17	2.1
2002	167	55	222	11.72	3.81	7.74	3.1

Table 3.7. Thyroid cancer cases among children born in 1986, and operated during 1990-2002 period.

Time of birth	Number	%
Born before 26.04.86	48	67.6
Born after 26.04.86 (cases “in utero”)	23	32.4
Total	71	100

Morphological analyses

Papillary histology constituted 95% of all thyroid carcinoma of the exposed (Table 3.8). Less common were follicular carcinomas (4%). C-cell (medullary) and anaplastic (or undifferentiated) cancer were diagnosed only in 0.9% and 0.1% of the patients, respectively. The relative frequency of the tumour types was about the same for all ages at operation.

Table 3.8. Distribution on pathology and gender in dependence on year of therapy.

Year at therapy	Number of thyroid cancer cases*							
	Papillary		Follicular		Medullary		Anaplastic	
	males	*females*	*males*	*females*	*males*	*females*	*males*	*females*
1986-1989	12	21	1	4	0	0	0	0
1990-1995	196	386	12	21	1	4	0	2
1996-2001	311	683	9	24	4	6	0	0
2002	55	155	1	7	0	2	0	0
Total	574	1245	23	56	5	12	0	2

* Four patients refused from therapy. The pathological diagnosis for them was based on the results of fine needle aspiration biopsy but not on histological study of removed thyroid tissue.

Three of the 17 medullary thyroid carcinomas had genetic predisposition (1 MEN2B and 2 MEN2A syndromes). Two of the anaplastic carcinomas developed in patients with a prolonged history of thyroid nodules. No case of undifferentiated carcinoma was diagnosed in patients at age 15 at therapy.

The majority of cases were primary microcarcinomas: Thirty-five per cent of the patients had tumors with a size equal or less than 1 cm (Table 3.9). Nevertheless, two third of the cases had positive lymph nodal involvement at the time of therapy. This required extended surgery and could be considered as an index of the aggressive nature of the disease in young patients.

There was no statistical difference between the exposed and the unexposed concerning extrathyroidal growth: T4 was diagnosed in 13.1% of cases among the exposed and in 7.5% of the unexposed. This indicates that spontaneous and radiogenic carcinomas have a similar invasive and metastatic potential.

The frequency of small carcinomas (≤ 1 cm) was particularly high (56%) in the period 1990 – 1995 (Table 3.10)

Table 3.9. TNM UICC classification of thyroid carcinoma among those aged 0-18 at the time of the accident.

TNM class	N0	N1a	N1b	Total	(%)
T1a	307	205	60	572	30
T1b	44	26	30	100	5
T2a	265	293	220	778	41
T2b	24	54	89	167	9
T3a	13	5	7	25	1
T3b	0	1	6	7	0
T4a	21	81	88	190	10
T4b	3	15	60	78	4
Total	677	680	560	1917	100
(%)	35	35	29	100	

Table 3.10. Size distribution of papillary carcinomas among those aged 0-18 at the time of the accident.

Year at therapy	Number of tumours with given size (cm)*							
	≤ 1	1.1 - 2	2.1 - 3	3.1 - 4	4.1 – 5	5.1 - 6	> 6	Total
1986-1989	8	12	9	1	1	0	0	31
1990-1995	207	208	77	35	13	2	2	544
1996-2001	373	683	120	38	7	7	2	952
2002	93	405	24	7	0	0	1	211
Total	681	711	230	81	21	9	5	1738

* In 81 cases the tumor size could not be detected, because the patients underwent repeated surgery for relapses after primary procedures in regional hospitals.

3.3 COMPARATIVE ANALYSIS OF CASE CHARACTERISTICS IN THE TWO COUNTRIES

Case numbers

Annual thyroid cancer cases in the two countries and in their highly contaminated areas have been compared in the frame of the present project (Jacob et al. 2002). There are similarities, but also significant differences.

Similarities. In both countries, the incidence rate started in 1990 to be significantly higher than the previous baseline level.

Differences. In Ukraine, there is a constant increase of the annual thyroid cancer incidence rate in the birth-year cohort 1968 – 1985 since 1990 (about 23 additional cases per year, see Table 3.1). In Belarus, however, there was a steep increase starting in 1990 until 1994 (about 27 additional cases per, see Table 3.6; the population of Belarus is by a factor of 5 smaller than the population of Ukraine), followed by a slower increase until 2002 (about 11 additional cases per year).

The thyroid cancer incidence in Gomel (most highly contaminated oblast of Belarus) was highest for age at operation of 10 years in the period 1992 to 1995, and for age at operation of 14 years in the period 1996 to 1999 (Figure 3.2). For older ages at operation (17 to 27 years in the period 1992 to 1995 and 21 to 31 years in the period 1996 to 1999) the number of cases

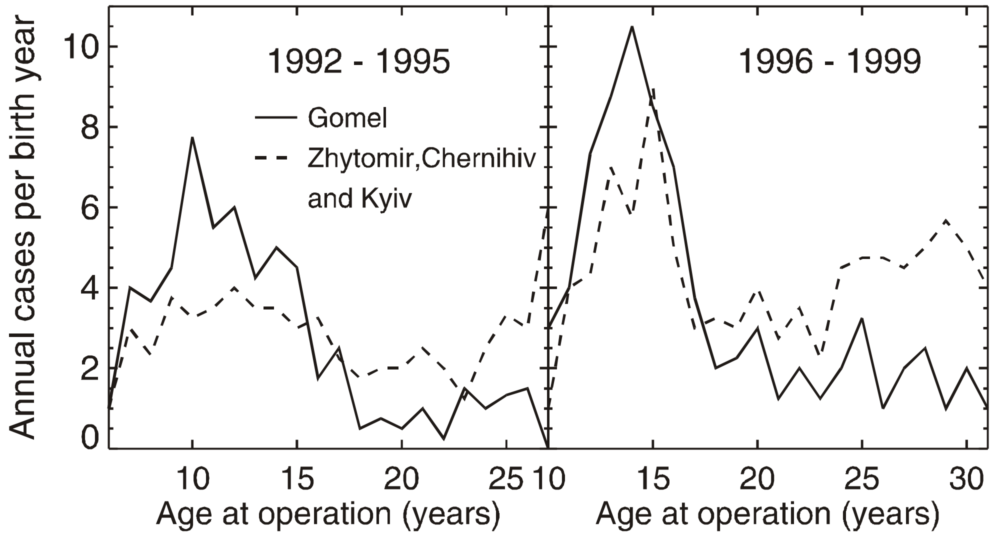

Fig. 3.2. Number of thyroid cancer cases as a function of age-at-operation as reported for the periods 1992 - 1995 and 1996 - 1999 for the birth cohort 1968 - 1985 of Gomel Oblast and of Zhytomyr, Chernihiv and Kyiv Oblasts including Kyiv City in Ukraine (from Jacob et al. 2002).

does not depend on age and the incidence in this age range is by factor of 7 - 8 smaller than in the peak. In the highly contaminated area of Ukraine, however, the incidence depends less on age at operation. An increase is observed for higher ages at operation which is mainly due to an increasing incidence among females.

The incidence among those with an age at exposure of 1 - 6 years is in Gomel by a factor of five larger than the incidence among those with an age-at-exposure of 13 - 18 years, the ratio of cases among females to cases among males is about the same in both age-at-exposure groups (Fig. 3.3). In the highly contaminated areas of Ukraine, however, the incidences in the two age-at-exposure groups differ less than by a factor 1.5, the ratio of cases among females to cases among males is considerably larger for the older ones.

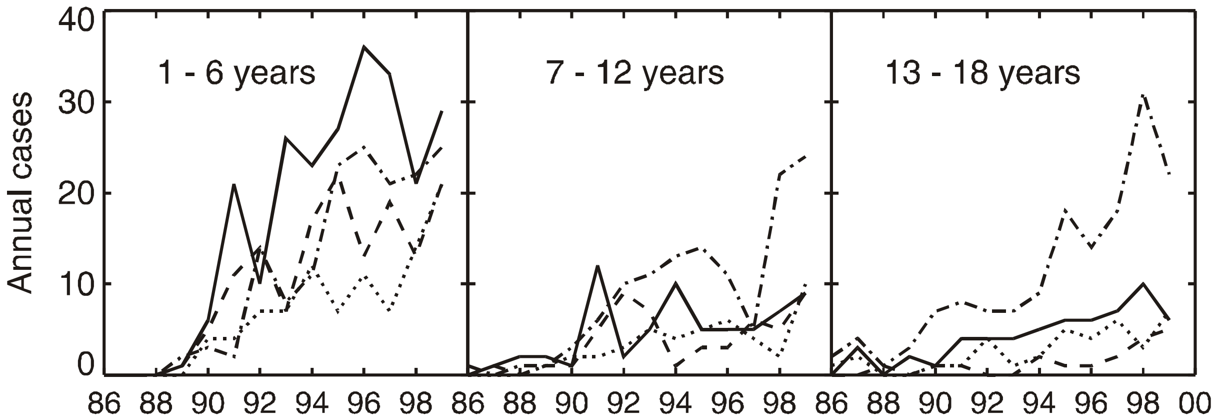

Fig. 3.3. Number of thyroid cancer cases reported for the period 1986 to 1999 to the registries for three birth cohorts of Gomel Oblast in Belarus (solid line for females and broken line for males) and of the Zhytomyr, Chernihiv and Kyiv oblasts including Kyiv City in Ukraine (broken line with dots for females and dotted line for males).

Morphological classification

Also concerning the morphological classification, there are similarities and significant differences.

<u>*Similarities*</u>. About 94% of the cases in the birth-year cohort 1968 - 1985 are papillary carcinomas (Tables 3.2 and 3.8). The frequency of large tumours (> 3 cm) was continuously decreasing in the period 1990 to 2002.

<u>*Differences*</u>. The frequency of follicular carcinomas increased in Ukraine from 1990 to 2002 from 3 to 6 %. In Belarus, however, there was no clear time dependence of the frequency of follicular carcinomas observed.

In Ukraine, the frequency of small papillary carcinoma (≤ 1 cm) was small and increasing (from 4% in 1990 to 20% in 2002). In Belarus, however, small papillary tumours were after 1989 frequent (40%), and their frequency did not depend on time. The frequency of large tumours (> 3 cm) is in Ukraine much higher than in Belarus.

4. RISK ANALYSES

Two kinds of analyses were performed:

- Incidence rates and average doses in the oblasts and larger cities of Ukraine and Belarus were analyzed in order to study temporal and regional dependencies of the baseline incidence
- Incidence rates and average dose in 1142 Ukrainian and Belarusian settlements, in which the ^{131}I activity in the human thyroid has been measured in May/June 1986, were analysed in order to derive excess risks.

4.1 ESTIMATION OF THE BASELINE INCIDENCE IN THE TWO COUNTRIES

This Section is a summary of a more extensive manuscript in Appendix 10.

Part of the increase of the thyroid cancer incidence in Ukraine and Belarus is due to an awareness of the influence of the Chernobyl accident on thyroid diseases, to the introduction of ultra sound devices, and to mass screening. The summary of published data on screening

Table 4.1. Number of thyroid cancer cases detected in various screening programs in Ukraine and Belarus. ATA indicates age at the time of the accident, ATS age at screening (see Appendix 10 for references).

Study	Area	Age group	Period	Number of cases
IPHECA	Gomel (Bel)	ATA ≤ 18	1990-1992	15
	Kyiv and Zhytomyr (Ukr)	ATS ≤ 15	1992-1994	5
Sasakawa	Gomel (Bel)	ATA ≤ 9	1991-1996	37
	Mogilev (Bel)	ATA ≤ 9	1991-1996	2
	Kyiv (Ukr)	ATA ≤ 18	1996-2000	25
	Zhytomyr (Ukr)	ATA ≤ 14	1996-2000	11
Belarus screening programme	Belarus	ATS ≤ 14	1990-1991	7
	Gomel (Bel)	ATS ≤ 18	2002	2
Ukraine-USA cohort study	Kyiv, Chernihiv and Zhytomyr (Ukr)	ATA ≤ 18	1998-2000	43
			2001-2002	21

programs in Table 4.1 shows, that in Belarus a total of 63 cases and in Ukraine a total of 105 cases was found in screening programs, which is less than 5% of the cases reported in the two countries.

It is the purpose of this Section to present thyroid dose estimates and cancer data for the birth-year cohort 1968 - 1985 in the different oblasts (regions) of Belarus and Ukraine, and to estimate the radiation-independent (baseline) component of the incidence. Different age-at-operation and calendar-year periods are analyzed separately for areas with high, middle and low baseline incidence.

MATERIALS AND METHODS

The present study uses data for two cities and the 25 oblasts of Ukraine and for two cities and the six oblasts of Belarus (Fig. 4.1).

Fig. 4.1 Study area in Belarus and Ukraine: 31 oblasts (regions) and four cities.

Thyroid doses

The derivation of average thyroid dose in Ukrainian regions is described in Section 2.1. Two independent methods were used to derive average thyroid doses in Belarusian regions (Sections 2.2.1 and 2.2.3). Those Sections do not differentiate between thyroid doses of females and males in Belarus. For the present analysis, the ratio of the doses of the two genders in Kyiv City was used to derive gender-specific doses $D_{s,i}^{city}$ for the birth cohort i in Minsk and Gomel City according to

$$D_{s,i}^{city} = D_{av,i}^{city} \cdot D_{s,i}^{K} / D_{av,i}^{K}, \tag{4.1}$$

with

$$D_{av,i}^{K} = (PY_{f,i}^{K} D_{f,i}^{K} + PY_{m,i}^{K} D_{m,i}^{K}) / (PY_{f,i}^{K} + PY_{m,i}^{K}), \tag{4.2}$$

where the index s can be f for females and m for males, and the index K stands for Kyiv. In the same way, gender-specific doses for the oblasts of Belarus were derived using the ratio of the doses of the two genders in Chernihiv Oblast. Kyiv City is the city, and Chernihiv Oblast the oblast with the largest number of measurements in Ukraine.

Population data

All calculations were performed with data for the age-gender structure of the population in 1986. Migration of people within Ukraine, Belarus and the Russian Federation did not influence the calculations, because all cases are attributed to the place of residence at the time of accident and cases operated in one of these countries are reported to the Chernobyl register of the country, where the person was living at the time of the accident. Errors due to loss of follow-up because of migration into other countries are considered to be small. Also, the loss of follow-up due to death is considered to be small, because the birth-year cohort 1968 - 1985 is still young.

The age-gender structure in the Ukrainian oblasts was taken from the All-Union (Former Soviet Union) census data for the years 1979 and 1989. A linear interpolation was applied to derive the population structure in 1986. The derivation of population data for Belarus for the year 1986 is described in Section 3.2.

Thyroid cancer cases

The data on thyroid cancer cases in Ukraine are described in Section 3.1, the cases in Belarus in Section 3.2. For the present analysis, thyroid cancer cases that were operated in the period 1986 – 2001 among the birth-year cohort 1968 – 1985 were analyzed.

Table 3.6 contains for Belarus 1694 cases for the period 1986-2001. From these, the following were excluded for the present analysis: 25 cases with unknown residence at the time of the accident, 30 cases with birth year 1967, and 57 cases with birth year 1986.

Areas of high, medium and low baseline incidence

The 35 oblasts/cities have been subdivided in three groups of high, medium and low baseline incidence. Figure 4.2 shows the results obtained with the dose estimates of FENIX (Section 2.2.1) and under the assumption of an excess relative risk of 20 Gy^{-1}. Similar results were obtained for the dose estimates with the radioecological model (Section 2.2.3), and also under the assumption of an excess absolute risk model.

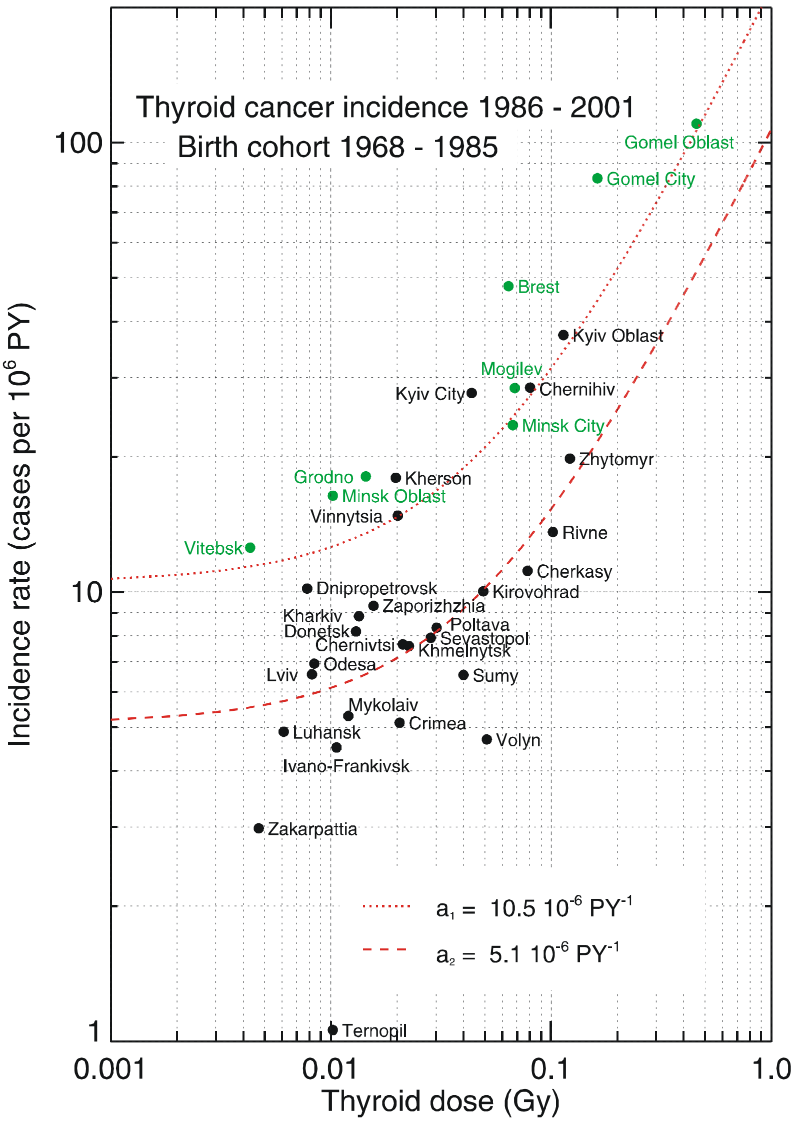

Fig. 4.2. Thyroid cancer incidence rate and average dose in 35 oblasts/cities of Belarus and Ukraine. The two lines represent two relative risk functions that subdivide the oblasts/cities in an upper, middle and lower group of baseline incidence rate.

Baseline incidence rates

In the three groups, Poisson regressions have been performed with the excess absolute risk model in the program *Epicure* in order to derive baseline incidence rates for the two genders, four different age groups, and four periods of operation years. Subsequently, the baseline incidence rates have been fitted with the program *Origin* to a function of age. These functions were used to assess the contribution of the baseline to the total thyroid cancer incidence rates in the two countries and in the higher contaminated areas.

RESULTS

Practically all regions of Belarus, and all regions with high contaminations belong to the groups of high baseline incidence. The estimated baseline incidence has the following characteristics (Fig. 4.3):

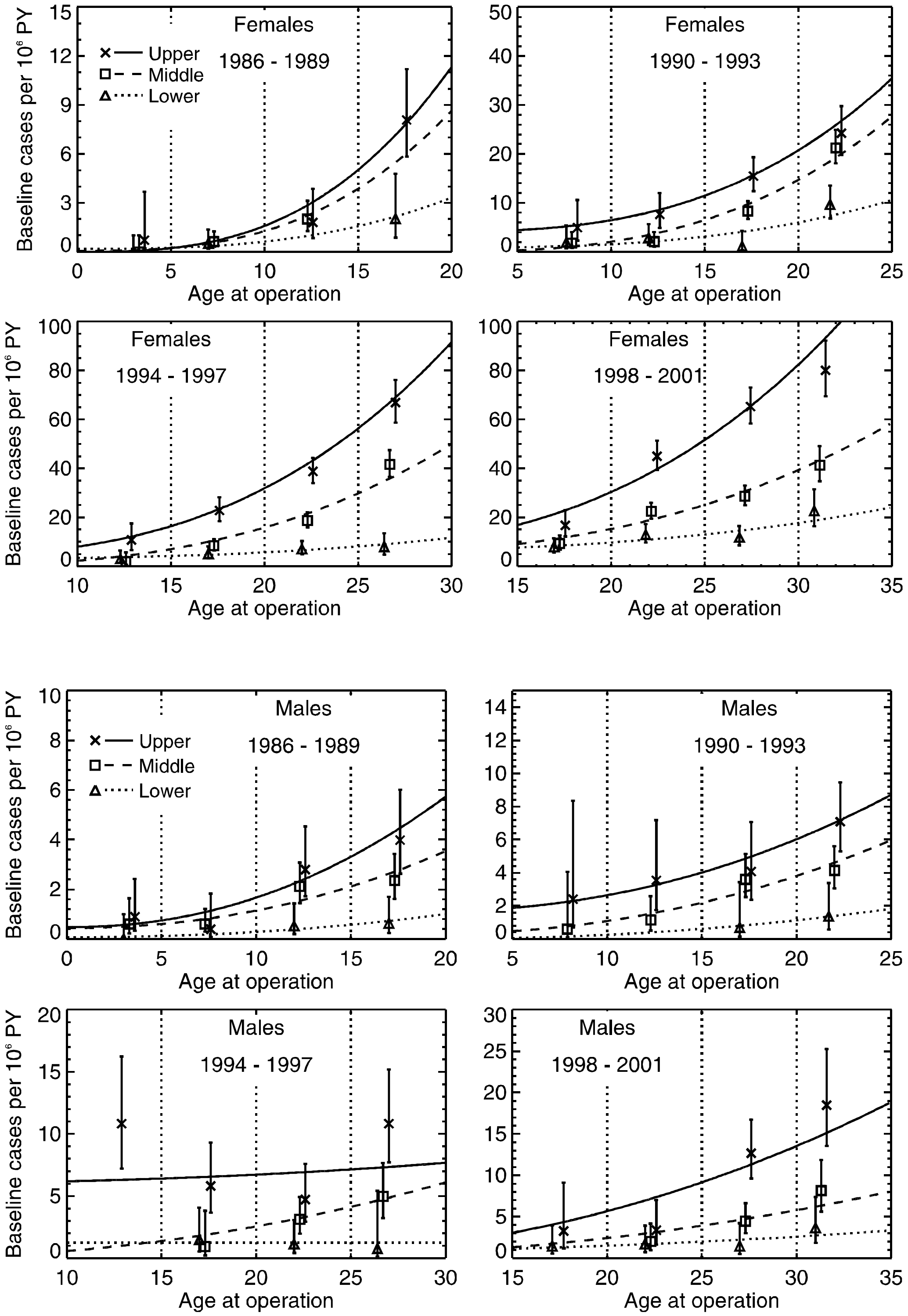

Fig. 4.3. Best estimates and geometric standard deviations (points with error bars) of the baseline thyroid cancer incidence. The lines represent analytical fits.

- The age-dependent term increases exponentially with age with an exponent of 2.8 for females and of 2.1 for males
- The baseline incidence is for 20-year old females by a factor of 5 higher than for 20-year old males
- In the upper group, the incidence is by a factor of 3.5 for females, and by a factor of 6 for males, higher than in the lower group
- Compared to the period 1986 – 1989, the baseline incidence in the subsequent years is in general increased by a factor of 2. Larger increases (factor 4) are observed for females in the upper group for the whole period 1990 - 2001, and in the lower group for the period 1998 - 2001. Practically no increase is observed for males in the middle group for the whole period 1990 - 2001, and in the lower group in the period 1990 - 1993.

The contribution of the baseline to the total thyroid cancer incidence is estimated to account in Ukrainre for 65%, in the three Northern oblasts of Ukraine (including Kyiv City) 45%, and in Belarus 30% (Fig. 4.4)

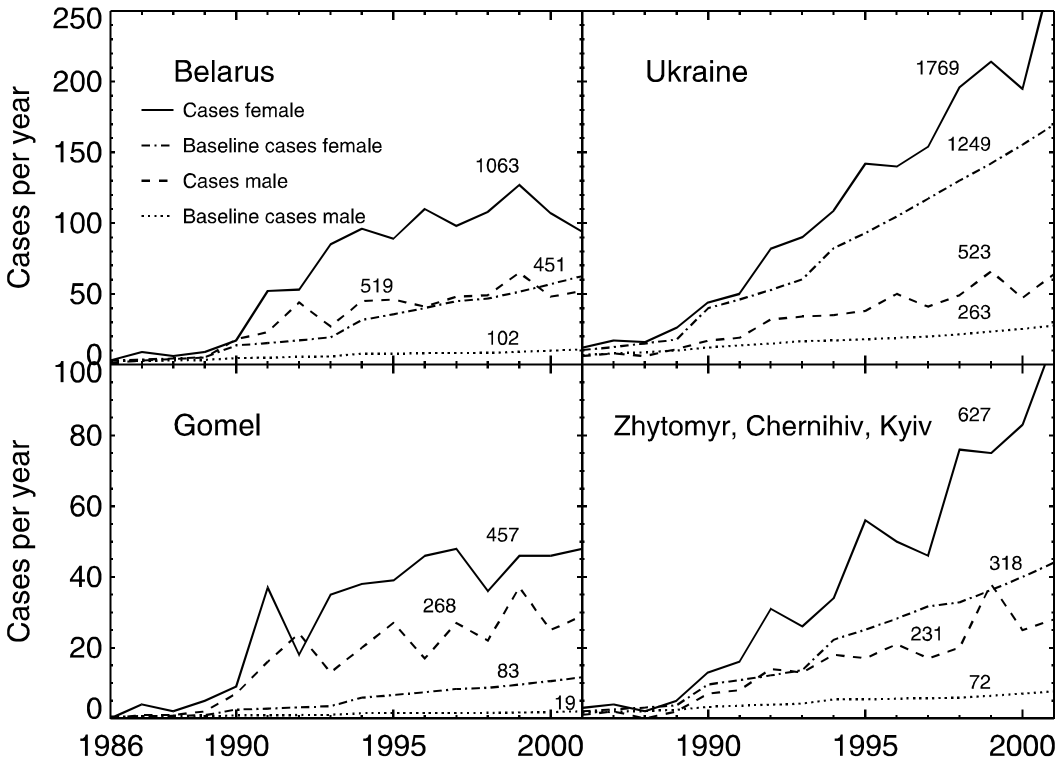

Fig. 4.4. Annual total and baseline number of thyroid cancer cases in the birth cohort 1968 - 1985 in Belarus and in Ukraine, and in the more affected areas. The figures at the curves give the cumulative numbers for the period 1986 - 2001.

4.2 EXCESS RISKS IN SETTLEMENTS WITH MORE THAN 10 MEASUREMENTS OF THE ^{131}I ACTIVITY IN THE HUMAN THYROID

It is the purpose of this Section to derive risk estimates for those who were at the time of the Chernobyl accident children or adolescents and lived in settlements, in which more than 10 measurements of the ^{131}I activity in the human thyroid have been performed in May/June 1986. This Section is a summary of Appendix 11.

MATERIALS AND METHODS

The present study uses data for 684 settlements in Ukraine and 458 settlements in Belarus (Fig. 2.7). Basic data used here for the two genders in the single birth-year cohorts 1968 – 1985 are

- estimates of the average thyroid dose in each of the settlements
- the number of persons living in the settlements in 1986
- among them the number of thyroid cancer cases operated in the period 1990 to 2001.

The loss of follow-up due to death in the period 1986 to 2001 has been neglected. It is small because the members of the cohort are quite young during the period of observation. The loss of cases due to migration is also considered to be small, because thyroid cancers of people, who were exposed as children or adolescents by the Chernobyl accident and who were operated in Belarus, Russia or Ukraine, should be reported to the registry of the country where the person lived at the time of the accident.

Thyroid dose

Ukraine. The methodology of deriving average doses from the measurements of the ^{131}I activity in the human thyroid is described in Section 2.1**.** The 95% range of average age- and gender specific thyroid doses in the 684 settlements is 0.015 – 0.36 Gy. There are a few small settlements with considerably higher thyroid doses (Fig. 2.8), up to 17 Gy for 1-year old boys.

Belarus. Two different methodologies of deriving age-dependent thyroid doses, as described in Sections 2.2.1 and 2.2.2, were applied, because there are larger uncertainties in the dosimetry for Belarus than for Ukraine. In Belarus as opposed to Ukraine, the measurements were performed with detectors, which were not shielded against radiation coming from other parts (than the thyroid) of the human body or from contaminated clothes.

For Belarus, only estimates of gender-averaged doses were available. As described in Section 4.1, gender dependencies as found in Ukraine for Kyiv City and for Chernihiv Oblast were transferred to Belarusian cities and villages, respectively.

The 95% range of average age- and gender specific thyroid doses in the 485 settlements in Belarus is similar for the two dosimetric models, 0.03 – 0.99 Gy. As in Ukraine, there are a few small settlements with considerably higher thyroid doses, up to 17 Gy for 1-year old boys according to the FENIX methodology (Section 2.2.1), and up to 15 Gy according to the GSF methodology (Section 2.2.3).

Both countries. For settlements close to the boundary of the two countries, comparable dose values have been derived by the dosimetric approaches in the two countries (Fig. 2.7). In total, the study comprises 41 112 ecologic units (1142 settlements, 18 age-at-exposure groups, 2 genders), and about 194 000 measurements of the ^{131}I activity in human thyroids were used to derive average doses in these ecologic units. The 95% range of average age- and gender specific thyroid doses in the 1142 settlements is 0.017 – 0.69 Gy (Fig. 2.8).

Population data

Population data for 1986 were derived from census data for the years 1979 and 1989, and from age-gender specific death rates (Appendix 11). In the 684 Ukrainian settlements, there were 1005 thousand children and adolescents in 1986 in the 36 age- and gender groups. Most of the children and adolescents lived in Kyiv. High doses occurred mainly in small settlements (Fig. 4.5).

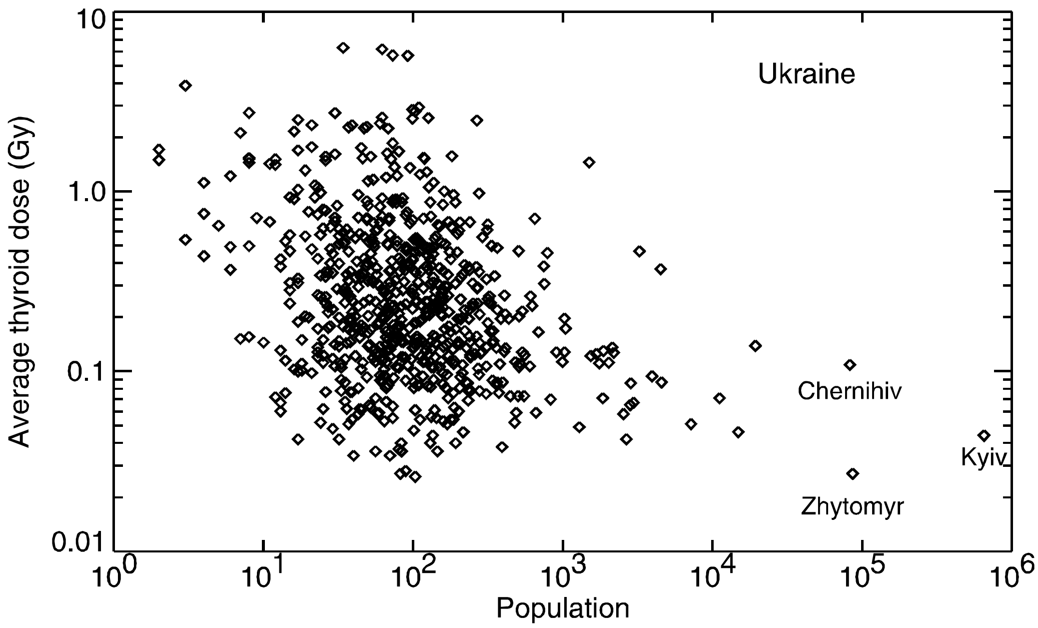

Fig. 4.5. Number of children and adolescents in 1986, and their average thyroid dose in 684 Ukrainian settlements with more than 10 measurements of the ^{131}I activity in the human thyroid.

There were 629 thousand children and adolescents in 1986 in the 36 age- and gender groups of the 458 Belarusian settlements. Most of the children and adolescents lived in Minsk. As in Ukraine, high doses occurred mainly in small settlements (Fig. 4.6).

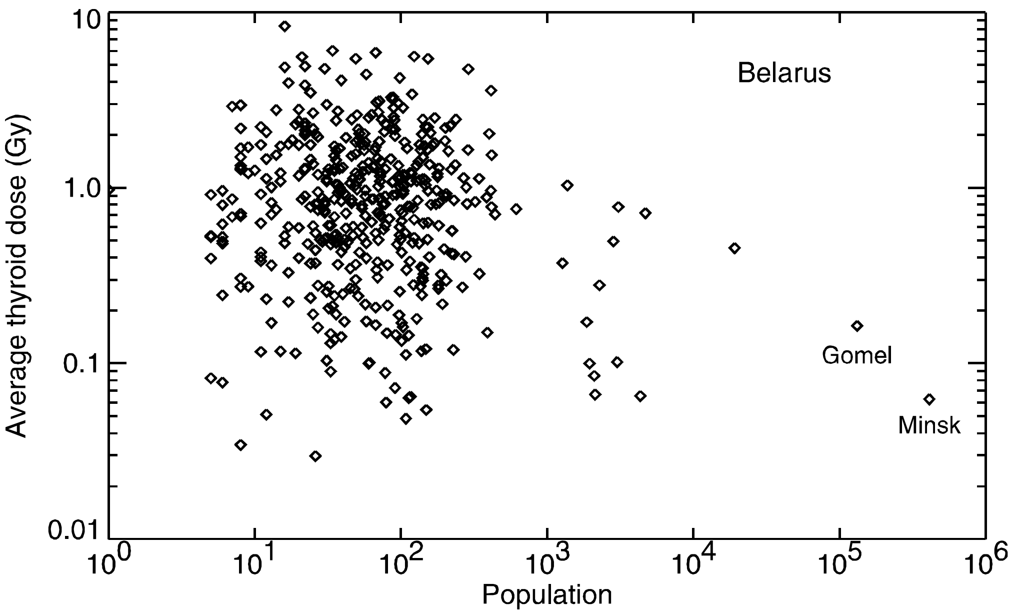

Fig. 4.6. Number of children and adolescents in 1986, and their average thyroid dose in 458 Belarusian settlements.

Thyroid cancer cases

Ukraine. The thyroid cancer registry and characteristics of the cases are described in Section 3.1. In total, 514 thyroid cancer cases have been reported for the period 1990 - 2001 and the birth-year cohort 1968 - 1985 in the 684 Ukrainian settlements, 379 cases of females and 135 of males. As for whole of Ukraine, the number of annual cases in the 684 Ukrainian settlements increases linearly since 1990 (Fig. 4.7).

The incidence rate is for the youngest (birth years 1982-85) 52 cases per 10^6 person-years, for other birth cohorts it is about 40 cases per 10^6 person-years. There is an indication that the incidence rate increases again for older ages. The ratio of female to male cases is about 2 for the younger ones (1978-85), and about 4 for the older ones (birth years 1968-77).

Belarus. The thyroid cancer registry is described in Section 3.2. In total, 581 thyroid cancer cases have been reported for the period 1990 - 2001 and the birth-year cohort 1968 - 1985 in the 485 Belarusian settlements, 370 cases of females and 211 of males. The number of annual cases started to increase steeply in 1990 (Fig. 4.7). In contrast to the Ukrainian settlements, the increase rate was not constant over the whole period up to 2001. It became – as for whole of Belarus - smaller in the middle of the 90ies.

The incidence rate is for the youngest (birth years 1984 - 1985) 133 cases per 10^6 person-years, decreases first with age at exposure, and has then an approximately constant value of about 55 cases per 10^6 person-years for the birth-year cohorts 1978 - 1969. The ratio of female to male cases is about 1.6 for the youngest ones (1980 - 1985), 1.2 for the birth-year cohort (1976 - 1979), and increases to 4 for the older ones (birth years 1968 - 1971).

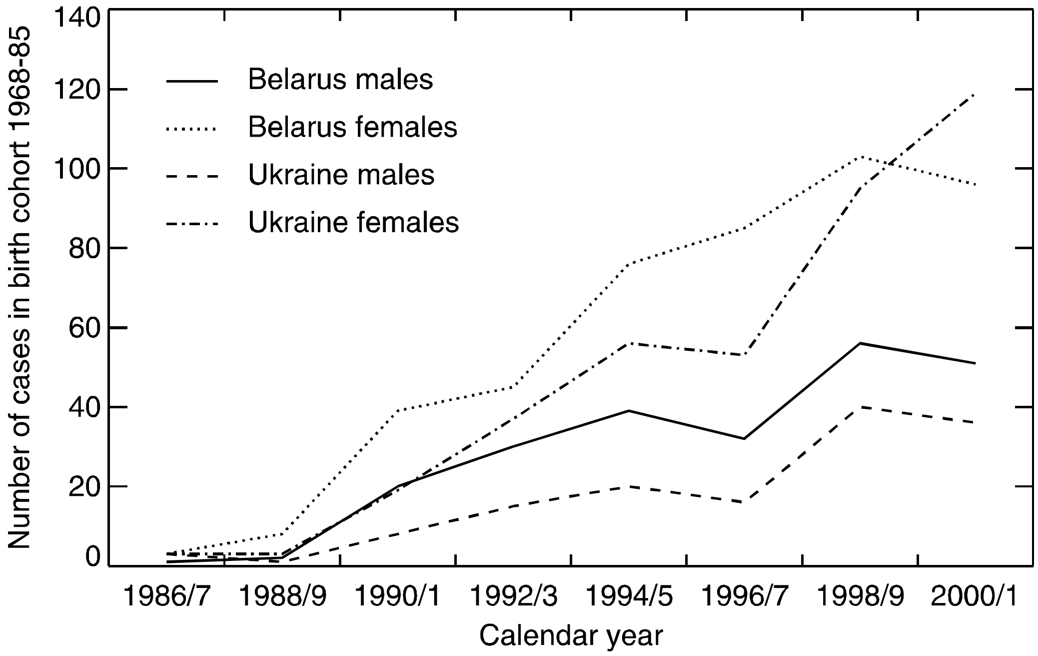

Fig. 4.7. Thyroid cancer cases among the birth-year cohort 1968 - 1985 in 684 Ukrainian and 458 Belarusian settlements in dependence of the operation year.

Analysis of data

Poisson regressions were performed with the excess absolute risk model

$$\lambda(d) = \exp(\beta_0) + \beta_1 \cdot d, \qquad (4.3)$$

with the excess relative risk model

$$\lambda(d) = \exp(\beta_0)(1 + \beta_1 \cdot d), \qquad (4.4)$$

and with a quadratic model

$$\lambda(d) = \exp(\beta_0) + \beta_1 \cdot d + \beta_2 \cdot d^2, \qquad (4.5)$$

where $\lambda(d)$ is the incidence rate for thyroid dose d, and β_i are fit parameters. The regressions were performed with the program AMFIT of the software package EPICURE (Hirosoft International Corporation, Seattle, WA).

RESULTS

Excess absolute risk (EAR) per dose

The EAR per thyroid dose (GSF, Section 2.2.2) in the period 1990 - 2001 for the birth cohort 1968 - 1985 in all 1142 settlements is estimated for females to 3.1 (95% CI: 2.6; 3.6) cases

Table 4.2. Excess risk estimates (best estimates and 95% confidence intervals) for the thyroid cancer incidence in the period 1990 – 2001 and the birth-year cohort 1968 - 1985 in 684 Ukrainian and 458 Belarusian settlements. Analyses were performed with two different sets of dose estimates for Belarus (by FENIX, Section 2.2.1, and by GSF, Section 2.2.2).

Area/dosimetry	EAR per dose (10^4 PY Gy)$^{-1}$			ERR per dose (Gy^{-1})		
	females	males	both	females	males	both
Ukraine	2.0 (1.2; 2.8)	1.4 (0.9; 2.0)	1.6 (1.2; 2.1)	4.1 (2.1; 6.1)	14 (4; 25)	5.6 (3.4; 7.7)
Belarus/GSF	3.7 (3.1; 4.4)	3.0 (2.5; 3.4)	3.3 (2.9; 3.7)	9.6 (5.8; 13.5)	199 (-566; 964)	17 (10; 23)
Belarus/FENIX	3.4 (2.8; 4.1)	2.7 (2.2; 3.2)	3.0 (2.6; 3.4)	8.2 (5.0; 11.4)	78 (-55; 210)	14 (9; 18)
Both countries/GSF	3.1 (2.6; 3.6)	2.4 (2.0; 2.8)	2.7 (2.4; 3.0)	7.2 (5.3; 9.1)	42 (13; 71)	11 (9; 13)
Both countries/FENIX	2.9 (2.5; 3.4)	2.3 (1.9; 2.6)	2.6 (2.3; 2.9)	6.6 (4.9; 8.4)	36 (14; 58)	10 (8; 12)

per 10^4 PY-Gy, and for males to 2.4 (95% CI: 2.0; 2.8) cases per 10^4 PY-Gy (Table 4.2). The estimates for Ukraine are significantly smaller (one sided Gauss-test: $p < 0.001$) than for Belarus.

The estimates obtained with the two different dosimetric systems are similar. Best estimates of the EAR per dose obtained with the dose estimates of GSF are 4 – 11% higher than those obtained with the dose estimates of FENIX.

Dependence on age at exposure. The EAR per dose decreases continuously with increasing age at exposure. For Belarus and for both countries combined, the best estimate of the EAR per dose is larger by a factor of 1.9 – 2.6 for age at exposure 1 - 6 years than for age at exposure 13 - 18 years. The difference is significant ($p < 0.008$). For Ukraine, the EAR per dose is not significant for age-at-exposure 13 - 18 years.

Dependence on time after exposure. The EAR per dose increases continuously over the period of observation. For Belarus and for both countries combined, the best estimate of the EAR per dose is larger by a factor of 1.5 – 2.1 for the period 1998 - 2001 than for the period 1990 - 1993. The difference is significant ($p < 0.04$). For Ukraine, the EAR per dose is not significant for the period 1990–93 of operation years.

Shape of dose response. In general, the best estimate of the quadratic term according to eq. (4.5) is negative and contributes less than 8% to the EAR at thyroid doses of 1 Gy. Exceptions are found in the 684 Ukrainian settlements for males and for both genders combined. Here the best estimate of the quadratic term is positive, but not significantly different from zero.

Excess relative risk (ERR) per dose

Based on the FENIX dose estimates for Belarus, the ERR per thyroid dose in the period 1990 - 2001 for the birth cohort 1968 - 1985 in all 1142 settlements is for females 6.6 (95% CI: 4.9; 8.4) Gy^{-1}, and for males 36 (95% CI: 14; 58) Gy^{-1} (Table 4.2). The estimates for females in Ukraine are significantly lower ($p = 0.006$) than for Belarus. No significant result was obtained for the excess relative risk for males in the 458 Belarusian settlements.

If the risk analysis is performed with the dose estimates of GSF, then similar results are obtained as in the analysis based on FENIX dose estimates. As for the excess absolute risk values, the excess relative risk values are a bit lower in the analysis with FENIX dose estimates.

In general, the estimated ERR values have a larger uncertainty than the estimated EAR values. For females and for both genders together, the ERR per dose decreases (in contrast to the EAR per dose) continuously over the period of observation. The best estimate of the ERR per dose is larger by a factor of 2.3 – 2.6 for the period 1990 - 1993 than for the period 1998 - 2001. The difference is significant ($p < 0.03$). Further, the ERR per dose decreases continuously with increasing age at exposure. The best estimate of the ERR per dose is larger by a factor of 9 – 15 for age at exposure 1 - 6 years than for age at exposure 13 - 18 years. The difference is significant ($p < 0.04$).

For the ERR of males, not enough significant results have been obtained to allow a derivation on the dependence on age at exposure or on the time after exposure.

DISCUSSION

Decrease of ERR with time after exposure

The decrease of the ERR with time after exposure is an indication that the spontaneous thyroid cancer incidence increases faster with age than the radiation induced cases in the cohort.

Dose uncertainties

The risk analysis presented here does not take into account dose uncertainties. The uncertainty of the average dose estimates for settlements in Belarus corresponds according to the two methods described in Sections 2.2.2 and 2.4 to a GSD of 1.6.

Uncertainties in Ukrainian settlements are assumed to be smaller than in Belarusian settlements, because shielded (versus unshielded) detectors have been used, and because there were in general better measurements conditions (inside versus outside houses, clean versus contaminated clothes, washing of persons before measurements).

For a linear dose response and a classical error structure, an underestimation of the excess risk values is expected if the dose uncertainty is neglected in the Poisson regression. There are two indications, however, why this underestimation is expected to be small for the current analysis.

- The dose uncertainty (GSD of 1.4 – 1.6) is small compared to the range of average doses used in the Poisson regression (GSD of about 2.5).
- In an earlier analysis (Jacob et al. 1999) calculations have been performed, which are similar from the methodological point of view as the present analysis. The results were compared with an independent method, a risk calculation with a Monte Carlo method, which took dose uncertainties in a simplified manner into account. No larger bias of the results was observed. Indeed, the EAR was in the Monte Carlo calculation by 10% higher than in the Poisson regression.

In summary, neglecting the dose uncertainties in the analysis is not expected to cause a larger bias on the risk estimates. However, confidence intervals are too small, and this has to be kept in mind in the evaluation of the significance of differences discussed in the Section Results.

Comparison with other studies in areas contaminated by the Chernobyl accident

Several risk analyses have been performed with data for the whole country of Ukraine (*e.g.*, Likhtarev et al. 1999), or for the whole country of Belarus (*e.g.*, Kenigsberg et al. 2002). Because of the higher reliability of dose estimates, results of the present analysis are compared here only with previous analyses of data for settlements with relatively good dosimetry.

Jacob et al. (1999) obtained for the thyroid cancer incidence in the period 1991 – 1995 in 2122 settlements in the highly contaminated area of Belarus plus Minsk and Gomel city an estimate of the EAR per dose of 2.1 (95% CI: 1.0; 4.4) cases per 10^4 PY-Gy. The best estimate of the present analysis is by 30% higher, the difference is, however, not significant (p

= 0.24). The results of Jacob et al. (1999) on the dependence of the EAR per dose on age at exposure and on gender are consistent with the present analysis. Also, the two studies agree on a small and negative quadratic term in the dose-response relationship.

In accordance with the present study, Jacob et al. (2000) reported the EAR per dose in 2122 settlements in the highly contaminated area of Belarus plus Minsk and Gomel city to increase with time after exposure. An increase by a factor 1.5 was reported for the period 1994 – 1996 compared to the period 1991 – 1993.

Comparison with risks after external exposures

The pooled study of thyroid cancer after external exposures during childhood (Ron et al. 1995) resulted in an estimate of the EAR per dose of 4.4 (95% CI: 1,9; 10.1) cases per 10^4 PY-Gy and of the ERR per dose of 7.7 (95% CI: 2.1; 28.7) Gy^{-1}. These results are close to what has been obtained in the present study: an EAR per dose of 2.7 (95% CI: 2.4; 3.0) cases per 10^4 PY-Gy and of the ERR per dose of 11 (95% CI: 9; 13) Gy^{-1} (Table 4.2). Since the EAR per dose was found to increase, and the ERR per dose to decrease with time after exposure, it can be expected that a study with a longer period of observation will result in best estimates of the risk values that are even closer to the results for external exposures than the results of the present study.

5. SUMMARY

Dosimetry

Ukraine. Based on measurements of the ^{131}I activity of the human thyroid, which have been performed in May/June 1986, thyroid doses due to the Chernobyl accident have been estimated for 130 thousand Ukrainian persons. The data were used to estimate the average dose for the two genders and for the 18 birth-year cohorts 1968 – 1985 in settlements with more than 10 of such measurements. The population structure in 1986 was assessed for 684 of these settlements with in total 1005 thousand children and adolescents. The estimated 95% range of average age- and gender specific thyroid doses in the settlements is 0.015 – 0.36 Gy. There are a few small settlements with considerably higher thyroid doses, up to 17 Gy for 1-year old boys.

A radioecological model has been developed to estimate age- and gender specific thyroid doses in all Ukrainian settlements. The ratio of model to measurement results was approximated by a function of the ^{137}Cs activity per unit area. This function was applied to the model results for all Ukrainian settlements. Based on these data, age- and gender specific doses were calculated for Ukrainian oblasts, and for Kyiv and Sewastopol city. In five oblasts (Zhytomyr, Kyiv, Rivne Chernihiv and Cherkasy) the average dose exceeded 0.035 Gy.

Belarus. Based on measurements of the ^{131}I activity of the human thyroid, which have been performed in May/June 1986, thyroid doses due to the Chernobyl accident have been estimated for 126 000 Belarusian persons. Two different methods (FENIX and GSF) were used to estimate the average dose for the 18 birth-year cohorts 1968 – 1985 in settlements with more than 10 of such measurements. With the exception of 10 settlements, the two methods agreed within a factor of two. The population structure in 1986 was assessed for 485 of the settlements with in total 629 thousand children and adolescents. Gender specific doses were derived by applying the ratio of female to male doses in Kyiv City to the Belarusian cities, and the ratio in Chernihiv Oblast to the Belarusian villages and towns. The estimated 95% range of average age- and gender specific thyroid doses in the settlements is 0.03 – 0.99 Gy. As in Ukraine, there were a few small settlements with considerably higher thyroid doses.

Age-specific thyroid doses in Belarusian settlements were calculated with an improved version of the semi-empirical model (in settlements with not more than 10 measurements of the ^{131}I activity) and with a newly developed radioecological model (all settlements). Gender specific doses were derived by applying the ratio of female to male doses in Kyiv City to the Belarusian cities, and the ratio in Chernihiv Oblast to the Belarusian villages and towns. Based on these data, age- and gender specific doses were calculated for Belarusian oblasts, and for Minsk and Gomel City. The two methods agree within a factor of two for all oblasts, for Minks City, however, the radioecological model is by a factor of 2 lower, and for Gomel City by a factor of 1.6 higher than the estimate, which is based on the measurements. In Gomel Oblast and in Gomel City the average dose exceeded 0.15 Gy.

Criteria for the reliability of the ecologic study. No systematic difference between the dose estimates for Ukrainian and Belarusian settlements with more then 10 measurements of the ^{131}I activity in the human thyroid could be observed. Indeed, the dose estimates for settlements close to the border of the two countries are quite close.

The uncertainty of age specific doses in the single settlements is in general characterised by a geometric standard deviation (GSD) of 1.6. The variability of individual doses within the age groups of the single settlements has been estimated to be characterised by a GSD of 2.3. The variability of the age-gender specific doses in the settlements with more than 10 measurements of the ^{131}I activity in the human thyroid was estimated to be characterised by a GSD of 2.0. According to these estimates, two criteria for a reliable ecologic study are fulfilled: The variability of the average doses for the ecologic units is

- considerably larger than the uncertainty of the average doses
- larger than the variability of the individual doses within the ecologic units.

The difference of the 95 percentile and the 5 percentile of the distribution of the age- and gender-dependent doses in the 1142 study settlements is 0.4 Gy (Fig. 2.8). Assuming an excess relative risk per dose of 10 Gy^{-1}, the incidence in the upper dose group is expected to be by a factor of five larger then in the lower dose group. Thus other risk factors play compared to the radiation a negligible role.

Spatial interpolation. A feasibility study on interpolating the ^{137}Cs activity per unit area in Belarusian settlements demonstrated that the spot of 308 South-Eastern settlements with ^{131}I measurements (sample settlements) is suited for an interpolation of results to derive dose estimates in adjacent settlements (target settlements) by geostatistical methods. The remaining Belarusian settlements are not suited, because high-dose settlements were preferentially sampled.

A geostatistical interpolation method was developed and applied to the South-Eastern Belarusian and the Ukrainian settlements. A "leaving-one-out" cross-validation showed that the average thyroid dose was predicted correctly in 837 of the 901 sample settlements (93%) within a factor of 2.5. On the other hand, there is a systematic overestimation of small doses and underestimation of high doses, which would lead to a bias in a risk analysis that is based on interpolated data.

Thyroid cancer data

Ukraine. The Thyroic Cancer Registry contains for the post-Chernobyl period (1986 - 2002), 2674 records of thyroid cancer cases in patients born in 1968 - 1986. The number of thyroid cancer cases increased with the time after the accident. The increase was most pronounced in those who were children aged up to 15 during the Chernobyl accident. In the period 1986 – 1989, the thyroid cancer incidence rate for children at the time of the accident was 0.12 cases per 10^5 PY. In 1990-1995 it had increased by a factor of 6, in 1996-2001 by a factor of 14, and in 2002 by a factor of 18. The ratio of female to male cases increased with age at the time of accident: from 3 for children to 4.6 for adolescents. The ratio increased also with age at surgery. It was 2 for those born after 1986.

In all age groups for the birth cohort 1968 -1985 and for all periods of observation, more than 92% of the cases were papillary carcinomas. For all age groups and all periods of observation, papillary carcinomas from 1 to 3 cm in diameter were dominant. Extrathyroidal spreading was reported for 44% of the papillary tumours. For any size of tumours, extrathyroidal spreading of carcinomas was more often reported for children than for adolescents and young adults. The percentage of papillary carcinoma with extrathyroidal spreading decreased with time elapsed after the accident for any size of tumour. Regional metastases were reported for 50% of the tumours. The highest percentage of regional metastases was observed in children, and the lowest in young adults. The percentage of regional metastases decreased with time elapsed after the accident for any size of tumour.

Belarus. The thyroid cancer registry contains records on 1916 cases in the period 1 June 1986 to 31 December 2002 for the birth-year groups 1968 – 1986. Since 1990, a significant increase of the thyroid cancer incidence has been observed. About twice as much thyroid cancer cases are observed for females compared to males. There is no significant sign of a change of this ratio with time after exposure.

Papillary histology constituted 95% of all thyroid carcinoma. The relative frequency of the tumour types was about the same for all ages at operation. Thirty-five per cent of the patients had tumors with a size equal or less than 1 cm. Nevertheless, two third of cases at therapy had positive lymph nodal involvement.

Comparative analysis of the two countries. The following similarities were observed in the two countries: In both countries, the incidence rate started in 1990 to be significantly higher than the previous baseline level. About 94% of the cases are papillary carcinomas. The frequency of large tumours (> 3 cm) was continuously decreasing in the period 1990 to 2002.

There are, however, also significant differences: In Ukraine, there is a constant increase of the annual thyroid cancer incidence rate. In Belarus, there was a steep increase starting in 1990 until 1994, followed by a slower increase until the end of 2002. Also, dependences of the incidence rates on gender, age at exposure and age at surgery are different. The frequency of follicular carcinomas increased in Ukraine from 1990 to 2002 from 3 to 6 %. In Belarus, however, there was no clear time dependence of the frequency of follicular carcinomas observed. In Ukraine, the frequency of small papillary carcinoma (≤ 1 cm) was small and increasing (from 4% in 1990 to 20% in 2002). In Belarus, however, small papillary tumours were after 1989 frequent (40%), and their frequency did not depend on time. The frequency of large tumours (> 3 cm) is in Ukraine much higher than in Belarus.

Risk analyses

Baseline incidence in the two countries. Data are analyzed for Kyiv and Sewastopol City and 25 oblasts (regions) in Ukraine, and for Minsk and Gomel City and 6 oblasts in Belarus. Case data were thyroid cancers operated in the period 1986 - 2001 among the birth-year cohort 1968 – 1985, allocated to the place of residence at the time of the accident. The 35 oblasts/cities were subdivided in an upper, middle and lower group of baseline thyroid cancer incidence. Poisson regressions were performed to estimate baseline incidence rates in the three groups. Compared to 1986 - 1989, the baseline rate in the later periods is in general increased by about a factor of 2. The increase is more expressed for females in the upper group, and less expressed for males in the middle group. The baseline cases are assessed to contribute about 65% to the thyroid cancer incidence in Ukraine, and about 30% to the incidence in Belarus. For females, the baseline contributes significantly more to the total incidence than for males.

Excess risks in settlements with more than 10 measurements of the ^{131}I activity in the human thyroid. Data are analysed for 684 settlements in Ukraine and 458 settlements in Belarus. In each of the settlements more than 10 measurements of the ^{131}I content in human thyroids had been performed in the period May/June 1986. Based on the measurement data, average thyroid doses due to the Chernobyl accident were assessed for every birth year in the birth-year cohort 1968 -1985. Census data from 1979 and 1989, and mortality rates in the period 1986 -1989 were used to derive the population structure in 1986. Case data were numbers of operations of pathologically confirmed thyroid cancers in the period 1986 - 2001 taken from registries that include the place of residence at the time of the accident. The excess absolute risk (EAR) per thyroid dose in all 1142 settlements is estimated for females to 3.1 (95% CI: 2.6; 3.6) cases per 10^4 PY-Gy, and for males to 2.4 (95% CI: 2.0; 2.8) cases per 10^4 PY-Gy. The excess relative risk (ERR) per dose is for females 7.2 (95% CI: 5.3; 9.1) Gy^{-1}, and for males 42 (95% CI: 13; 71) Gy^{-1}. The estimates for Ukraine are significantly lower than for Belarus ($p < 0.007$). The EAR per dose decreases with increasing age at exposure and increases with time after exposure. The ERR per dose decreases with time after exposure. The results agree within the confidence limits with excess risks that have been reported for external exposures during childhood.

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